NASA CONTRACTOR REPORT

NASA CR-930

NASA CR-930

N68-17591
(ACCESSION NUMBER)
146
(PAGES)
(NASA CR OR TMX OR AD NUMBER)
(THRU)
1
(CODE)
17
(CATEGORY)
FACILITY FORM 602

OXIDATION RESISTANT MATERI
FOR TRANSPIRATION COOLED
GAS TURBINE BLADES

I. Sheet Specimen Screening Tests

by Fred W. Cole, James B. Padden, and Andrew R. Spen

Prepared by
BENDIX CORPORATION
Royal Oak, Mich.
for Lewis Research Center

GPO PRICE $
CFSTI PRICE(S) $
Hard copy (HC) 3.00
Microfiche (MF) .65
ff 653 July 65

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1968

NASA CR-930

OXIDATION RESISTANT MATERIALS FOR TRANSPIRATION COOLED GAS TURBINE BLADES

I. Sheet Specimen Screening Tests

By Fred W. Cole, James B. Padden, and Andrew R. Spencer

Prepared under Contract No. NAS 3-7269 by
BENDIX CORPORATION
Royal Oak, Mich.

for Lewis Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

PRECEDING PAGE BLANK NOT FILMED.

FOREWORD

The work described herein was done by the Bendix Corporation under NASA Contract NAS 3-7269. It was conducted under the technical management of Mr. Albert E. Anglin, Jr., with Mr. Jack B. Esgar as research advisor. Both are from the Airbreathing Engines Division, NASA Lewis Research Center.

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

Twelve alloys were selected and tested in sheet metal form to compare their suitability for use as transpiration cooled gas turbine blade materials. The alloys were N 155, TD nickel, TD nickel-chromium, Bendel 65-35, Chromel A, DH 242, GE 1541, Hoskins 875, RA 333, Hastelloy X, Udimet 500, and Haynes 25. Screening tests consisted of cyclic furnace oxidation at 1400, 1600, 1800, 2000, 2100, and 2200°F for 4, 16, 64, 100, 200, 300, 400, 500, and 600 hours exposure time. Total oxidation and spalling were determined for each specimen along with variation in room temperature mechanical properties and microstructure. Electron beam welding feasibility was also investigated. Three "best-compromise" alloys were selected for later testing as wires to determine suitability for manufacturing space-wound or woven porous transpiration cooling materials.

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

SECTION		PAGE
1	Summary	1
2	Introduction	3
3	Alloy Selection and Procurement	5
4	Experimental Procedure	7
4.1	Specimen Preparation	7
4.2	Oxidation Cycle	7
4.3	Specimen Examination and Testing	8
4.3.1	Oxidation and Spall	8
4.3.2	Thickness and Surface Examination	9
4.3.3	Metallographic Examination	9
4.3.4	Tensile Tests	10
4.4	Electron Beam Welding	10
5	Results and Discussion	11
5.1	Oxidation and Spall	12
5.2	Thickness and Surface Examination	14
5.3	Metallographic Examination	14
5.4	Tensile Tests	16
5.5	Electron Beam Welding	16
6	Conclusions	18

TABLE		
3-1	Alloy Analysis	21
4-1	Metallographic Etchant Schedule	22
5.5-1	Mechanical Properties	23
6-1	Comparison of Extrapolated Alloy Properties	19

FIGURE		
4.1	Specimen and Test Schematic	24
5.1-1	Oxidation Resistance Comparison, 1400°F	25
5.1-2	Oxidation Resistance Comparison, 1600°F	26
5.1-3	Oxidation Resistance Comparison, 1800°F	27
5.1-4	Oxidation Resistance Comparison, 2000°F	28
5.1-5	Oxidation Resistance Comparison, 2100°F	29
5.1-6	Oxidation Resistance Comparison, 2200°F	30
5.1-7	Spalling Resistance Comparison, 1600°F	31
5.1-8	Spalling Resistance Comparison, 1800°F	32
5.1-9	Spalling Resistance Comparison, 2000°F	33
5.1-10	Spalling Resistance Comparison, 2100°F	34
5.1-11	Spalling Resistance Comparison, 2200°F	35
5.4-1	Mechanical Properties Comparison, 1400-1800°F	36
5.4-2	Mechanical Properties Comparison, 2000-2200°F	37
6-1	Extrapolated Oxidation Resistance Comparison	38
6-2	Extrapolated Spalling Resistance Comparison	39
6-3	Extrapolated Penetration Resistance Comparison	40

PAGE

APPENDIX

1 Numerical Data Tabulation. 41
2 Alloy Oxidation Plots. 69
3 Metallographic Examination 95
4 Oxidation Penetration Plots. 121
5 Tensile Test Data Plots. 135

INVESTIGATION OF OXIDATION RESISTANT MATERIALS FOR TRANSPIRATION COOLED GAS TURBINE BLADES

Part One
SHEET SPECIMEN SCREENING TESTS

by Fred W. Cole[1], James B. Padden[2], and Andrew R. Spencer[3]

THE BENDIX CORPORATION
Filter Division

1 SUMMARY

Twelve alloys were selected and tested as sheet metal specimens to compare their suitability for use in transpiration cooled gas turbine blade materials. The object of this investigation was to provide engineering data for specifying metal alloys used in space-wound (Poroloy) and woven wire (Rigimesh, Poroplate) porous structures. Alloys chosen from 56 candidate alloys were:

1. N 155. . . . . 21Cr-20Ni-20Co-3Mo-2.5W-Fe
2. TD nickel. . . . . $2ThO_2$-Ni
3. TD nickel-chromium . . . . $2ThO_2$-20Cr-Ni
4. Bendel 65-35 . . . . 3 spinel-35Cr-Ni
5. Chromel A. 20Cr-Ni
6. DH 242 . . . . 20Cr-1Cb-Ni
7. GE 1541. . . . . 15Cr-4Al-1Y-Fe
8. Hoskins 875. . . . . 23Cr-6Al-Fe
9. RA 333 . . . . 18Cr-3Mo-3W-3Co-Fe
10. Hastelloy X. 22Cr-18.5Fe-9Mo-1.5Co-Ni
11. Udimet 500 . . . . 19Cr-19.5Co-4Mo-3Ti-3Al-Ni
12. Haynes 25. . . . . 20Cr-15W-10Ni-Co

This selection was based on considerations of past and present practice, existing problems to be solved, and survey correspondence.

Cyclic oxidation tests were conducted on sheet metal coupons 6 x 0.5 x 0.06 inch in size, individually held in covered zircon ceramic "test tubes", with a separate specimen for each alloy-temperature-time combination. All coupons were polished and then "sintered" in hydrogen for two four-hour cycles at 2100°F before oxidation testing to simulate fabrication practice. Test temperatures of 1400, 1600, 1800, and 2000°F were used for all twelve alloys. Five alloys were also tested at 2100 and 2200°F. Exposure times at each temperature were 4, 16, 64, 100, 200, 300, 400, 500, and 600 hours. All specimens were cooled to room temperature after each time cycle to simulate the cyclic, rather than steady-state, heat exposure expected in hot gas turbine service.

Each alloy specimen was measured to determine total oxidation weight gain, spalling oxide loss, gross thickness change, and oxide layer thickness. All

[1]Chief Project Engineer, Filter Division
[2]Project Engineer, Filter Division
[3]Staff Metallurgist, Research Laboratories Division

specimens, including "as-received" and "as-sintered" samples, were metallographically examined to determine significant morphology changes caused by oxidation and heat exposure. After cyclic oxidation each specimen was tensile tested at room temperature to determine ultimate and yield strength and percentage elongation. Electron beam welding tests were conducted on each alloy to determine feasibility for future production fabrication. Welds were evaluated by metallographic examination and tensile testing.

Three alloys: TD nickel-chromium, DH 242, and Hastelloy X, were selected on the basis of these tests for future investigation as fine wire suitable for transpiration cooling material fabrication. Selection criteria included oxidation and spalling resistance, ductility retention, and fabrication feasibility. The chromium-aluminum-iron alloy class, GE 1541 and Hoskins 875, were among the three best alloys in oxidation and spalling resistance but the latter showed lower ductility retention. Simple chromium-nickel solid-solution alloys, TD nickel-chromium, DH 242, Chromel A, and Bendel 65-35, showed excellent oxidation resistance, in that order, along with very good ductility retention. More complex superalloys, Hastelloy X, and Udimet 500, showed good oxidation resistance and good ductility retention. Other alloys were judged to be less suitable according to these criteria.

2 INTRODUCTION

This experimental investigation was conducted to evaluate and select metal alloys which are particularly suitable for fabricating transpiration cooling materials used in turbine blades and similar engine components. Therefore, major emphasis was placed on measuring oxidation resistance and retention of mechanical properties for the selected alloys after cyclic furnace heating in air. This report describes test results and conclusions derived from testing sheet metal specimens. A second and final report will describe a similar test program conducted on 0.005 inch diameter wire specimens drawn from the three best alloys selected on the basis of the sheet metal specimen test results.

Advanced gas turbine engines operate at higher turbine inlet temperatures than present uncooled engines. Air-cooled turbine blades and other components are utilized in nearly all new engines under development. Convection cooling, which is currently being most extensively used, transfers heat from the component wall by parallel or impingement flow of the coolant air. Film cooling, often used in series with convection cooling, insulates the component from the hot gas stream by injecting coolant air through multiple holes or slots in the wall. These cooling methods increase engine efficiency by allowing higher temperature operation, but efficiency improvement is diminished by increased consumption of coolant air. Maximum gains require efficient cooling with minimum cooling air. Transpiration cooling techniques offer excellent potential for reducing the coolant flow required and further improving engine efficiency.

Transpiration cooling may be considered as an extension of convection and film cooling concepts. Cooling air flows through a porous component wall. The porous wall structure provides extended surface area for convective heat exchange from the wall to the coolant. At the outer wall surface the coolant is injected into the hot gas stream boundary layer through many small, closely-spaced pores. The resultant coolant film insulates the porous wall from the hot gas stream. The porous wall structure characteristics of large surface area to volume ratio and small pore size, which provide for most efficient transpiration cooling, aggravate problems of structural degradation and porous flow-channel plugging caused by oxidation corrosion during operation. Oxidation which may be considered minor for solid or sheet metal components might seriously affect an otherwise equivalent porous structure.

Oxidation resistance is a primary criterion for transpiration cooling material specification. Therefore, major emphasis in this investigation was placed on determining comparative total oxidation and oxide spalling for the selected test alloys. Other alloy characteristics such as retention of mechanical properties after cyclic heating and electron beam welding feasibility as a fabrication method were also tested. All tests were designed and interpreted from the viewpoint of application to transpiration cooling materials engineering. However, much of the data reported for cyclic oxidation of superalloys should also be useful for other engineering applications.

The scope of this report is directed toward the initial selection of twelve candidate alloys, testing and evaluation of those alloys in the context of their application to space-wound (Poroloy*) and woven wire (Rigimesh*, Poroplate*) transpiration cooling materials, and final selection of three "best-compromise" alloys for further testing as fine wires. Before testing, specimens were heat-treated at 2100°F to simulate the typical manufacturing sintering operation. Cyclic oxidation screening tests were conducted at 1400, 1600, 1800, 2000°F and at 2100 and 2200°F for the five best alloys. The lower temperatures are comparable to the actual metal temperatures held in present transpiration cooled turbine blade tests. The higher temperatures represent the range expected for advanced gas turbine engines where cooling air may leave the compressor at 1200°F. Time intervals of 4, 16, 64, 100, 200, 300, 400, 500 and 600 hours were chosen to allow reasonable data extrapolation of expected service life. All specimens were cooled to room temperature at each time interval to simulate the cyclic oxidation conditions expected in service. Each specimen was contained in a separate zircon ceramic thimble or "test tube" designed to catch oxide scales which spalled from the metal surface, and to allow air circulation for oxygen replenishment. Spalling can contribute to oxidation plugging and eventual failure of transpiration cooling materials.

After exposure, the twelve sheet specimens were tested to determine their comparative characteristics. Total oxidation weight gain and oxide spalling were measured by weighing. Thickness change of the specimen because of oxidation and spalling was measured with a micrometer. Oxide surface characteristics showing spalls or blisters were photographically recorded. Oxide layer thickness and intergranular penetration were measured from metallographic sections which were later etched to show morphology variations. Changes in mechanical properties due to oxidation and over-aging were found by tensile testing to determine yield strength, ultimate strength, and percentage elongation. Separate electron beam welding feasibility tests were conducted on each alloy and were evaluated by tensile testing and metallographic examination of the weld-zone section.

---

*Poroloy and Poroplate are registered trade-names describing space-wound wire and laminated woven wire mesh transpiration cooling materials, respectively, manufactured by The Bendix Corporation, Filter Division. Rigimesh is a registered trade-name describing laminated woven wire mesh materials manufactured by the Pall Corporation, Aircraft Porous Media Division.

3 ALLOY SELECTION AND PROCUREMENT

Specification of the initial twelve sheet specimen screening test alloys was based on examination of past experience and anticipation of future requirements. Particular emphasis was placed on engineering feasibility from both technical and economic viewpoints. Therefore, present state-of-art alloys, primarily from the superalloy and resistance-heating alloy families, were chosen:

1. N 155. . . . . 21Cr-20Ni-20Co-3Mo-2.5W-Fe
2. TD nickel. . . . . $2ThO_2$-Ni
3. TD nickel-chromium . . . . . . $2ThO_2$-20Cr-Ni
4. Bendel 65-35 . . . . 3 Spinel-35Cr-Ni
5. Chromel A. 20Cr-Ni
6. DH 242 . . . . 20Cr-1Cb-Ni
7. GE 1541. . . . . 15Cr-4Al-1Y-Fe
8. Hoskins 875 . . . . 23Cr-6Al-Fe
9. RA 333 . . . . 18Cr-3Mo-3W-3Co-Fe
10. Hastelloy X. 22Cr-18.5Fe-9Mo-1.5Co-Ni
11. Udimet 500 . . . . 19Cr-19.5Co-4Mo-3Ti-3Al-Ni
12. Haynes 25. . . . . 20Cr-15W-10Ni-Co

The alloy numbers one through twelve assigned in this list are referenced throughout the report for alloy identification.

Alloy selection included consideration of literature data and elimination of impractical candidates. Expected oxidation resistance and high temperature strength were important factors. Refractory metals such as tungsten and noble metals such as platinum were considered impractical because of respective problems of oxidation attack and cost or supply. Similarly, development of new alloy systems or coatings was considered to be outside the scope of this work. Casting-type superalloys with superior properties were not included because of the difficulty in producing fine wires from them. Manufacturing considerations, as well as chemical and physical properties, were weighted in this selection. A total of 56 candidate alloys were reviewed.

N 155 was chosen because of its fair oxidation resistance and strength, and because its previous use in many types of transpiration cooling materials provides a base-line for comparison with other alloys. TD nickel and TD nickel-chromium promised excellent high temperature strength because of the thoria dispersion, along with good oxidation resistance for the latter alloy. Bendel 65-35 is a nickel-chromium alloy type with a $Al_2O_3 \cdot MgO$ spinel dispersion to provide ductility. Chromel A and DH 242 are similar representatives of the nickel-chromium solid-solution system with good oxidation resistance and ductility at the expense of high temperature strength. GE 1541 and Hoskins 875 typify the iron-chromium-aluminum resistance-heating alloys with high oxidation resistance, but lower strength and low ductility for the latter alloy. RA 333, Hastelloy X, Udimet 500, and Haynes 25 represent the several families of highly developed superalloys based on iron, nickel and cobalt.

The twelve selected alloys were purchased from the mills as sheet, strip, or ribbon approximately 0.060 inch thick. All alloys were specified according to applicable AMS or proprietary specifications and were certified by their vendor. After receipt of the materials and verification of their documentation, each alloy was analyzed by an independent laboratory to verify its composition. The results of this analysis are shown in Table 3-1 which compares the specified or certified composition for each alloy with the composition determined by sampling and spectrographic or wet chemical analysis. All alloys were accepted as complying with the nominal specification limits. Suppliers for each alloy are also listed.

4 EXPERIMENTAL PROCEDURE

Test procedures were designed to simulate, within practicable limits, those conditions expected to arise in future utilization of the alloys. Sheet specimens were polished and heat-treated to simulate the surface finish and microstructure of fabricated transpiration cooling materials. Furnace oxidation tests were conducted with cyclic heating and cooling to roughly simulate service conditions in a hot gas turbine. All alloys were tested together to allow direct comparison of results.

4.1 Specimen Preparation

Specimens were sheared to a nominal 0.5 x 6 inch size, allowing extra material for later grinding to a uniform and common size. Surface contamination was removed by sonic cleaning in hot trichlorethylene followed by acetone rinsing. After cleaning, the specimen coupons were heat-treated to simulate the sintering cycle usually employed to bond space-wound or woven wire-type transpiration cooling materials. While this treatment of sheet specimens may not produce the microstructure expected for fine wires, the resultant grain growth is more nearly simulative than the original wrought structure. Sheared coupons were placed in perforated mild steel trays with Fiberfrax separators to prevent actual sintering of adjacent strips. The simulated sintering cycle consisted of two four-hour periods at 2100°F in dry hydrogen (below -80°F dewpoint) with intermediate cooling to room temperature after sintering. Alloys GE 1541, Hoskins 875, and Udimet 500 appeared to be slightly oxidized because of their aluminum content; other alloys were bright.

After sintering, all coupons were polished with a power belt sander using successively finer grades of abrasive and finishing with #320 grit silicon carbide. A bright, smooth surface having better than 10 micro-inch RMS finish was produced. The strips were finish-ground to 0.5 ± 0.010 x 6.0 ± 0.010 inch size as shown in Figure 4-1. Final sonic cleaning was accomplished in hot trichlorethylene with an acetone rinse to avoid chloride residues. Each specimen was measured to determine its actual size and area. Thickness was measured with a calibrated precision micrometer using a pin anvil. Measurements were made at three points along the specimen length to the nearest 0.0001 inch. Specimen weight was determined to ± 0.1 mg with an analytical balance.

4.2 Oxidation Cycle

Specimens were contained in zircon ceramic thimbles during oxidation cycling to collect spall and avoid extraneous contamination. The thimbles are shaped like test tubes 0.88 O.D. x 0.75 I.D. x 7 inches long with a flat disc lid and having four 0.13 inch air-circulating holes drilled near the top and bottom as shown in Figure 4-1. Preliminary tests with mild steel samples showed that this arrangement allows sufficient air convection so that results are essentially equivalent to open air oxidation. Zircon base ceramic material ($ZrO_2 \cdot SiO_2$, Leco 528-125) was chosen to minimize fluxing or other interaction between metal oxides and the thimble. All thimbles were hard fired at 2900°F and baked out at 1400°F to constant weight before using. Coupons were placed in the thimbles with four-point minimum contact at the corners of the specimen. Each thimble and thimble-coupon combination was weighed to 0.1 mg before exposure.

Thimbles were vertically supported in 2 x 7 array on a special rack made from 0.19 inch diameter type 330 stainless steel wire to minimize contact between thimbles and rack. Twelve openings were used for thimbles containing each of the twelve alloys. One opening was used for an empty control thimble to check thimble weight changes due to heating. The last opening was used for a dummy thimble containing an inserted thermocouple to simulate and monitor actual specimen temperature. Ten racks were arranged on a movable skid-pan, allowing one specimen set for each time cycle and one spare or check set. Thermocouples were #24 Ga chromel-alumel for 1400 and 1600°F tests and #14 Ga chromel-alumel at the higher temperatures. One thermocouple from each rack was connected to a central potentiometer-recorder which continuously monitored the temperature of each specimen set. Automatically controlled and recording electric furnaces with 13 x 16 x 48 inch type 330 stainless steel muffles, loosely blocked with fire-brick, were used to maintain temperatures within $\pm1\%$ of the nominal setting. Two furnaces were used to expedite testing.

Oxidation cycling procedure consisted of adjusting the furnace to the required temperature with a proportional controller set to minimize temperature fluctuation. Prepared sample skid-pans were loaded with a fork-lift dolly into the furnace and power was increased and then backed-off to "meet" the temperature and minimize lag. Full furnace recovery time was less than one hour for all runs. After exposure for the required time, the skid-pan was removed and all sample sets were cooled to room temperature in about one hour in still air under ambient conditions. The assigned rack was then removed to a dessicator for future examination and the other samples were returned to the furnace. This procedure was repeated for each time interval of 4, 16, 64, 100, 200, 300, 400, 500, and 600 hours and for each temperature of 1400, 1600, 1800, 2000, 2100 and 2200°F.

4.3 Specimen Examination and Testing

After oxidation exposure, each sample set of twelve alloys was stored in a dessicator pending later weighing, examination and tensile testing. The following characteristics were determined for each alloy after each temperature-time oxidation period.

(1) Total oxidation weight gain and oxide spall weight
(2) Thickness changes and surface oxide characteristics
(3) Oxide penetration and alloy microstructure
(4) Mechanical properties at room temperature

<u>4.3.1 Oxidation and spall</u>. - Each alloy coupon-thimble combination was weighed to 0.1 mg to determine total oxidation and amount of oxide spalling. Data were determined by direct weighing and by indirect or difference weighing. The weighing procedure followed this sequence:

(1) thimble + spall + coupon
(2) coupon
(3) thimble + spall
(4) spall
(5) thimble

The thimble, spall and coupon (1) were weighed together. Then the coupon (2) was removed, along with adherent oxides, and weighed separately. The remaining spall and thimble (3) were weighed. The spall (4) was removed from the thimble with a soft brush and weighed. Finally, the empty thimble (5) was weighed alone. These redundant weighings provide for checking errors due to accident or oxide loss because of sticking to the thimble.

Total weight gain and spall were determined from these data. Direct weights were used except where indirect or difference weights showed less scatter or error. Example calculations are shown below:

	Direct	Indirect
Spall weight	(4)	(3) - (5, initial)
Total weight gain	(2, final) - (2, initial) + (4)	(1) - (5, initial)

Initial thimble weights (5) were corrected to compensate for a small weight gain of the control thimble at the highest temperatures. Direct and indirect weight data should be equal and in most cases they were equal within expected experimental error. Spall weight sometimes exceeds total weight gain because spall consists of metal oxides while total weight gain consists of reacted oxygen only.

4.3.2 Thickness and surface examination. - After weighing, all specimens were re-measured with the micrometer at the same reference points shown in Figure 4-1 to determine gross changes in thickness due to oxidation and spalling. The specimens were sheared to provide samples for macrophotography, metallographic examination and tensile testing. Surface oxide characteristics were observed at low magnification and photographically recorded showing the progression of oxidation corrosion with time for each test temperature. Loose oxide spall was collected from each specimen and preserved.

4.3.3 Metallographic examination. - Metallographic samples were sheared from the top end (as held during oxidation) of each specimen shown in Figure 4-1 Shearing was used instead of the customary wet or dry abrasive cut-off wheel to avoid contaminating the oxide film with extraneous debris. Cut samples were mounted in a liquid, two-part casting resin. Specimens were segregated and classified according to their expected polishing and etching characteristics Each mount contained three to ten sample strips of the same alloy separated with thin type 302 stainless steel or Inconel 600 support strips to help preserve specimen edges. The strips were painted with liquid resin and bundled into a compact, wire-wrapped assembly to avoid bubbles between specimens. Liquid resin potting was used instead of conventional hot-press mounting to minimize damage to the fragile oxide layers.

The cured specimen mounts were ground back from the exposed specimen ends about 0.060 inch to obtain a representative specimen cross section. Normal finish grinding and polishing procedures were employed, using magnesium oxide for final polishing. Oxide layers were observed at 300X with a microscope using normal, reflected light. Oxide thickness was measured with a calibrated eye-piece reticule and average thickness was estimated over the entire specimen periphery. Photomicrographs at 300X were made showing a representative oxide layer for the 600 hour specimen of each alloy-temperature combination.

After oxide layer observations and measurements were completed, the 600 hour specimens were etched using the schedule reported in Table 4-1. Alloy morphology at the section center was observed and photographed at 500X using a microscope with normal lighting. Comparison specimens of each alloy in the "as-received" and "as-sintered" condition were also prepared and photographed. Electron beam welded specimens, discussed in Section 4.4, were similarly sectioned, polished and etched to show penetration and weld structure. Photomicrographs were made at 50X magnification.

4.3.4 Tensile tests. — The four-inch segment of the oxidized specimen coupon was used for tensile tests to show changes in mechanical properties caused by oxidation and heat exposure. Half-scale ASTM E-8 tensile test specimens, having a 1.000 x 0.250 gage section, were wet-ground from each sample. Specimens were pulled at 0.050 inch/minute on an Instron testing machine to provide a continuous stress-strain curve for each specimen. Ultimate tensile strength and yield strength (0.2% off-set) were determined on the basis of measured gross specimen thickness after oxidation exposure to allow data comparison between specimens. Elongation was measured from lay-out marks on the one-inch gage-length after fracture. Additional tests were conducted on "as-received" and "as-sintered" material for comparison purposes.

4.4 Electron Beam Welding

Electron beam welding feasibility tests were conducted on each alloy. Strip specimens, similar to those described in Section 4.1 "Specimen Preparation," were heat-treated and butt-welded together. Preliminary tests showed that a common welding schedule of 3 ma beam current at 100-130 KV with 0.025-0.040 inch circular beam deflection and a traverse speed of 30 inches per minute was adequate for all specimens. Two weld samples were prepared for each alloy. Metallographic samples were made by welding together two 0.5 x 0.5 inch strips and processing according to the methods given in Section 4.3.3 "Metallographic Examination." Tensile test samples were made by welding together two 0.5 x 2 inch strips and wet-grinding one-half scale ASTM E-8 configuration specimens with the weld-zone centered in the gage-length. Tensile tests were conducted as described in Section 4.3.4 "Tensile Tests."

5 RESULTS AND DISCUSSION

The purpose of this investigation was to provide supplementary engineering data for selecting alloys suitable for transpiration cooling applications. Three "best-compromise" alloys, TD nickel-chromium, DH 242 and Hastelloy X, were chosen from the twelve candidate alloys tested. Choice was based on considerations of cyclic oxidation resistance, retention of good mechanical properties (especially ductility) after oxidation and heat-aging, and manufacturing or fabrication feasibility. Further oxidation tests of these three alloys in 0.005 inch diameter wire form will be described in a subsequent report. The results reported in the present investigation are primarily intended to be used in transpiration cooling technology, but these data should also be useful for other applications. Alloy selection rationale based on these test results is discussed in the context of its application to space-wound (Poroloy) and woven wire (Rigimesh, Poroplate) transpiration cooling materials.

Oxidation resistance is a primary criterion for transpiration cooling material alloy selection. Maximum cooling efficiency requires a material structure with extended surface area and small, closely-spaced pores. The large internal surface area and small internal sections are susceptible to oxidation damage which may result in plugging or structural deterioration. Oxide growth within porous flow-channels or internal spalling of oxide scales restricts coolant air flow and causes localized over-heating which accelerates further oxidation. Corrosion of thin internal wires or walls reduces material strength and may ultimately cause structural failure. Minimum cooling with low coolant air consumption is desirable to maximize net engine efficiency gain. Therefore, transpiration cooled components should be used at the highest allowable temperature which does not cause excessive oxidation and functional degradation. The optimum design compromise for transpiration cooling material geometry is largely determined by the oxidation resistance of the metal alloy selected for construction.

Retention of strength and ductility after oxidation and heat exposure is also an important consideration for alloy selection. Most transpiration cooling materials are used as an outer heat-resisting layer or "skin" which is attached to a cooler supporting structure. The inner structure provides necessary mechanical strength for the component and conducts coolant air to the skin through ducts and plenums. Therefore, the skin is generally required only to "hold itself". Good stress-rupture properties are desirable, but strength is less important than oxidation resistance for transpiration cooling materials. Ductility retention during service is necessary. Some superalloys over-age after prolonged exposure to temperatures in the range of 1400 to 1600°F and become fairly brittle. This lack of ductility renders these materials more susceptible to foreign object damage or cracking from cyclic heating and cooling. Therefore, ductility retention is a major alloy property for this application.

Manufacturing and fabrication characteristics must also be considered in producing practical and economical transpiration cooled hardware. Most transpiration cooling materials are manufactured by sinter-bonding wire structures which are made by space-winding in a geometrically determined pattern or by stacking layers of woven mesh. Therefore, the selected alloy must be suitable for wire drawing and sintering. Comparatively brittle or non-homogeneous alloys are difficult to draw and alloys containing reactive elements such as aluminum or titanium are difficult to sinter. After manufacturing the skin must be formed and fastened to its supporting structure. Electron beam welding is commonly used in fabrication. Therefore, alloy weldability is an important consideration.

This investigation was designed to evaluate and compare the selected alloys according to oxidation resistance, mechanical stability and manufacturing characteristics, which are essentially pertinent for transpiration cooling material alloy specification. All test data were reduced and tabulated in Appendix 1, "Numerical Data Tabulation". Total oxidation weight gain and oxide spall weight are plotted as a function of time for each alloy with temperature as a parameter in Appendix 2, "Alloy Oxidation Plots". Selected photographs of surface oxides and photomicrographs of oxide layer sections, alloy microstructures, and electron beam weld zone sections are shown for each alloy in Appendix 3, "Metallographic Examination". Oxide layer thickness and penetration, determined by measurement of the metallographic sections are shown in Appendix 4, "Oxidation Penetration Plots". Mechanical property changes with exposure temperature are shown for each alloy at 100 hours and 600 hours cycling time in Appendix 5, "Tensile Test Data Plots".

5.1 Oxidation and Spall

Total oxidation weight gain was determined for specimens representing each alloy-temperature-time combination. Specific weight gain per unit area was calculated from both direct weighing data (net increase in the sum of coupon plus collected spall weights) and indirect or difference weighing data (net increase in total thimble plus specimen weights, corrected for thimble weight change). These data are plotted in Figures 5.1-1 through 5.1-6 which compare alloy oxidation resistance at each test temperature. Faired power-function plots on a log-log grid, showing specific weight increase as a function of time, were adequate to represent the test data. The resultant linear relationship for most alloy tests suggests that diffusion-controlled oxidation kinetics predominated, in which expected parabolic rate laws were modified by alloy complexity and oxide spalling at the higher temperatures. Direct weighing data was used from 1400 to 1600°F tests while indirect weighing data usually proved to be more reliable at higher temperatures. Oxide spalling and adherence to the test thimbles was more severe at temperatures above 1800 to 2000°F. The affect of increasing temperature on oxidation rate is shown for each alloy in Appendix 2, "Alloy Oxidation Plots".

Oxide spall weight was similarly determined for each specimen and expressed as specific weight per unit area. Spalling for each alloy is compared in Figures 5.1-7 through 5.1-11 for each significant test temperature. Spalling was not measurable within test accuracy limits at 1400°F and many alloys had insignificant spalling at 1600°F. Spall rate data are also represented by a linear plot on a log-log grid which suggests its dependence on the total oxidation rate. The affect of increasing temperature on spall rate is also shown for each alloy in Appendix 2.

The comparative oxidation and spall rates shown in Figures 5.1 through 5.11 are identified according to the alloy number sequence assigned in Section 3, "Alloy Selection and Procurement".

1. N 155
2. TD nickel
3. TD nickel-chromium
4. Bendel 65-35
5. Chromel A
6. DH 242
7. GE 1541
8. Hoskins 875
9. RA 333
10. Hastelloy X
11. Udimet 500
12. Haynes 25

At 1400°F the iron and nickel base resistance-heating type alloys (8, 6, 3, 5, 7) are shown to be most oxidation resistant in the order given when evaluated at the 600 hour mark. The longest oxidation times are considered to be most significant for engineering evaluation and selection of the better alloys. Consideration of the plotted slope of specific weight gain/time is also important: alloy 7 apparently has a high initial oxidation rate, which is quickly arrested when a protective oxide film is formed, and the resultant slope is nearly flat. Alloy 4, Bendel 65-35, was not tested at 1400°F. At 1600°F the same alloy types (3, 4, 5, 6, 7) show best oxidation resistance but in different sequence and at 1800°F the order of ranking (3, 7, 8, 5, 6) is again changed. At 2000°F alloys 3, 8, and 7 are clearly superior and superalloys 10 and 11 begin to contend with the nickel-chromium alloys 5 and 6.

Based on these comparisons, five alloys were chosen for further oxidation cycling at 2100 and 2200°F: TD nickel-chromium (3), DH 242 (6), Hoskins 875 (8), Hastelloy X (10), and Udimet 500 (11). Alloy 6 was chosen over similar alloy 5 because both alloys were comparable in oxidation resistance at 2000°F, and alloy 6 had been used to make transpiration cooling materials having good ductility retention. Alloy 8 was chosen over similar alloy 7 because the former showed slightly better oxidation resistance at 2000°F, and alloy 7 presented more difficult future manufacturing problems because of its yttrium content. At 2100°F the chosen alloys were ranked 3, 8, 10, 6, 11 and at 2200°F the order was changed to 3, 8, 6, 10, 11. Alloys 3, 6, and 10 were later chosen for further study as fine wires. Alloy 3 was consistently superior in high temperature oxidation resistance. Alloys 6 and 10 promised good oxidation resistance along with good mechanical and fabrication properties, already proven in manufacturing and testing transpiration cooling materials. Alloy 8 was not tested in wire form, despite its excellent oxidation resistance, because of its rapid loss of ductility on heating as shown by the tensile tests described in Section 5.4. Alloy 7 retained ductility after heating at 2000°F. Later testing and metallographic examination indicated that alloy 7 would have provided a better combination of oxidation resistance and ductility retention than alloy 8.

Spalling resistance is shown separately in Figures 5.1-7 through 5.1-11. Alloy ranking for least spalling closely follows that given for total oxidation resistance. Spalling was negligible for all alloys at 1400°F; at 1600°F spalling was measurable for alloys 4, 1, 9, and 10 only. At 1800°F ranking for least spalling was 8, 3, 7, 10, 12 and at 2000°F the order was changed to 7, 8, 3, 10, 6. At the higher test temperatures alloy ranking was 3, 8, 10, 6, 11 at 2100°F and 3, 8, 6, 10, 11 at 2200°F. The superalloys 10 and 11 showed sharply increased oxidation and spalling rates after about 300 hours exposure time.

5.2 Thickness and Surface Examination

Gross thickness changes measured with a micrometer are recorded in Appendix 1, "Numerical Data Tabulation". A general trend of increasing thickness with progressing oxidation was shown until spalling became significant. After this point localized scaling and spalling caused increasing data scatter. Oxide layer thickness and penetration measurements were, therefore, determined exclusively from metallographic sections. Gross thickness measurements when compared with oxide penetration measurements, provide a useful indication of progressive oxidation and remaining metal thickness as shown in Appendix 4, "Oxide Penetration Plots".

Surface oxides were examined for each specimen. Typical characteristics of color, texture or particle size, and magnetic properties are noted in Appendix 1. Photomacrographs of the 1800°F specimens were selected for reproduction in Appendix 3, "Metallographic Examination". This temperature showed visibly progressive oxidation corrosion for all alloys except TD nickel-chromium which is shown at 2200°F. These photographs help describe the qualitative character of oxide formation and spalling for each of the test alloys.

5.3 Metallographic Examination

Photomicrographs are reproduced in Appendix 3, "Metallographic Examination", which show the formation and penetration of the oxide layer for the 600 hour specimen at each significant test temperature. Specimens were selected, as indicated by captions, to show the probable useful range of temperature. These metallographic sections, and the other specimens exposed for shorter times, were measured to determine the data plotted in Appendix 4, "Oxide Penetration Plots" which show the relationship of specimen thickness change and oxide penetration as a function of cycling time for each temperature. Oxide layer thickness and observed penetration are recorded for each specimen in Appendix 1, "Numerical Data Tabulation". Internal microstructure and morphology changes resulting from exposure to successively higher test temperatures are also shown for the same 600 hour specimens in the photomicrographs of Appendix 3. Control specimens showing "as-received" and "as-sintered" microstructures are shown for each alloy. Electron beam weld zone sections, etched to show weld characteristics and microstructure, are also reproduced here.

Examination of the oxide layer and alloy microstructure photomicrographs of Appendix 3 shows progressive change with increasing temperature which may be correlated with alloy performance. The most oxidation resistant alloys retain comparatively thin, adherent oxide films with little integranular or internal oxidation. The beginning of substantial oxide penetration is associated with heavy spalling and an increase in spall rate which clearly defines the upper temperature limit for engineering utilization of the alloy. Similarly, microstructural changes may be compared with changes in mechanical properties and especially with changes in ductility which may affect alloy selection for some temperature ranges.

TD nickel-chromium (3) alloy (Figures A3-3), which exhibited the best oxidation resistance, has an initial medium-fine grain structure with a uniform but slightly clumped dispersion of thoria. Unresolved micro-sized thoria particles are probably also present. Simulated sintering heat-treatment caused no apparent change in this microstructure. Oxide layers are thin and uniform at temperatures up to 2000°F. Minor spalling begins in the range of 2000-2200°F, in association with increased oxide penetration and apparent internal oxidation. The oxide penetration plots of Appendix 4 show small penetration and slight total thickness growth which may be related to internal oxidation at the highest temperatures. Microstructural changes are minor over the entire temperature range of 1400-2200°F.

Hoskins 875 (8) and GE 1541 (7) alloys (Figures A3-8 and A3-7), which had excellent oxidation resistance, both changed in microstructure after sintering at 2100°F. Alloy 8 showed large grain growth from an initial fine grain, single-phase structure which was associated with drastic reduction in ductility. Alloy 7 had smaller grain growth with some spheroidizing of an initial two-phase structure and an increase in ductility. Both alloys formed thin adherent oxide films at temperatures up to 2000°F. Penetration and thickness changes were minimal. Internal oxidation and associated spalling was also low. Grain structure became slightly coarser with increasing temperature and ductility further decreased, although alloy 7 retained very good ductility.

DH 242 (6) and Chromel A (5) alloys (Figures A3-6 and A3-5), which had good oxidation resistance, both displayed marked grain growth after sintering. The original medium-grain matrix contained fine inclusions of primary carbides. Oxide growth and penetration became substantial above 1800°F, and was associated with heavy oxidation and spalling. Large thickness increases also appear and may result from extensive internal oxidation. Alloy 6 had slightly more weight gain but less spall and penetration than alloy 5 at the same temperatures. Both alloys showed some additional grain growth and ductility loss as temperatures increased but ductility retention was excellent, especially for alloy 6.

Hastelloy X (10) and Udimet 500 (11) alloys (Figures A3-10 and A3-11), which had fair oxidation resistance, were considerably changed in microstructure and mechanical properties by sintering. Alloy 10 had a fine grain structure with visible primary carbides. After sintering large grain growth was observed with a new boundary phase and some spheroidization, accompanied by reduced strength and ductility. Alloy 11 changed from a fairly large grain structure with a few primary carbides and a preferentially oriented fine precipitate to a similar structure with uniformly precipitated gamma prime. Strength was greatly decreased and ductility was increased because of this solutioning. Both alloys showed substantial oxidation attack above 1600°F with fairly heavy oxidation, spalling, and oxide penetration. Grain growth increased with increasing temperature, strength decreased, but ductility improved from comparatively low elongations in the 1400-1600°F range.

Other alloys were less satisfactory in oxidation resistance. Bendel 65-35 (4) alloy (Figures A3-4) showed little change in its fine grain, coarsely dispersed $Al_2O_3 \cdot MgO$ spinel structure after sintering, and oxidation resistance was good at 1600°F. But spalling and oxidation increased sharply at higher temperatures, where a second lot of the alloy was tested, and ductility decreased while thickness grew, indicating substantial internal oxidation shown in the photomicrographs. Haynes 25 (12) alloy (Figures A3-12) showed slight grain growth after sintering but initial strength was substantially reduced by annealing, Oxidation and spalling increased greatly at 1800 and 2000°F and ductility was minimized at 1800°F. Thickness increases at 1800 and 2000°F imply internal oxidation as shown by the oxide layer and internal microstructures. N 155 (1) and RA 333 (9) alloys (Figures A3-1 and A3-9) had large grain growth after sintering and comparable oxidation resistance, with greatly increased oxidation after 1600°F and evidence of penetration and internal oxidation. TD nickel (2) alloy (Figures A3-2) retained its finely dispersed thoria structure after sintering with little agglomeration. Oxidation and spalling was high, as expected, and became almost catastrophic above 1600°F. The photomicrographs show heavy, uneven oxide formation but little internal change although thickness growth occurred.

5.4 Tensile Tests

All tensile test data are tabulated in Appendix 1, "Numerical Data Tabulation", which gives ultimate strength, yield strength, and elongation for each specimen after oxidation cycling. Selected data at 100 hours and 600 hours exposure time is graphically displayed in Appendix 5, "Tensile Test Data Plots", which shows progressive changes in alloy mechanical properties with increasing exposure temperature. Mechanical properties of the alloys are compared at 600 hours for each test temperature in Figures 5.4-1 and 5.4-2. Changes in mechanical properties are related to corresponding changes in alloy oxidation attack and microstructure as indicated in Section 5.3, "Metallographic Examination".

TD nickel-chromium (3) had good ductility (about 20%) and fairly high yield strength (near 90 ksi) which were virtually unaffected by exposure to temperatures in the range of 1400-2200°F for up to 600 hours. DH 242 (6) and similar alloy Chromel A (5) had greater ductility (over 40%) and lower yield strength (near 30 ksi) which were only slightly reduced up to 2000°F. Hoskins 875 (8) had almost zero ductility after sintering and oxidation, and reached a maximum strength near 70 ksi at 1800-2000°F. GE 1541 (7) had good ductility (over 20-30%) and yield strength (over 40 ksi) which were somewhat reduced by exposure at the higher temperatures up to 2000°F. Hastelloy X (10) had fairly low ductility (below 10-20%) after aging at 1400-1600°F which improved at higher temperatures because of solutioning while yield strength dropped from over 40 ksi to about 30 ksi. Udimet 500 (11) had a minimum ductility (below 10%) and yield strength (about 70 ksi) at 1800°F with better properties above and below this temperature. Other alloys, which were not chosen for high temperature testing or wire-form tests, showed individual characteristics which may be seen by reference to Figures 5.4-1 and 5.4-2 and Appendix 4.

5.5 Electron Beam Welding

Electron beam welding feasibility was demonstrated for each alloy. Metallographic sections of typical butt-welded joints are shown in Appendix 3, "Metallographic Examination". Tensile test results for welded specimens are given in Table 5.5-1, "Mechanical Properties of Alloys" and graphically compared with other tensile test data in Appendix 5, "Tensile Test Data Plots". All alloys were welded but joint efficiency and microstructure varied considerably.

TD nickel-chromium (3) was difficult to weld and showed undercutting and agglomeration of the thoria dispersion. A second "cosmetic" pass was made to seal off porosity and improve the weld surface. Joint efficiency was over 90 percent based on room temperature yield strength but fracture occurred in the weld at only one percent elongation. DH 242 (6) was easily welded with a fine-grain homogeneous microstructure. Tensile test results for the welded specimen were comparable to those for the unwelded specimen and fracture occurred outside of the weld zone. Hastelloy X (10) was also easily welded with good joint efficiency and structure. Tensile fracture was ductile and out of the weld zone. Alloys GE 1541 (7) and Hoskins 875 (8) were easily welded with a resultant fine-grain microstructure but weld joint strength and ductility was fairly low. Comments on alloy weldability are summarized:

Alloy	Comments
N 155 (1)	Apparently sound weld easily obtained. There were no voids in a very fine as-cast structure.
TD nickel (2)	Not easily welded. There was undercutting on beam side of the weld and the microstructure showed partial agglomeration of thoria dispersion.
TD nickel-chromium (3)	Not easily welded. There was undercut on beam side of the weld. A cover pass was made at 90 KV, 5 MA, 15 IPM to seal porosity. Agglomeration of thoria dispersion and some porosity were revealed in the microstructure.
Bendel 65-35 (4)	Apparently sound weld with low porosity easily obtained. The weld zone was undercut on both sides, apparently because the spinel was expelled during welding.
Chromel A (5)	Apparently sound weld easily obtained, with medium to fine grain structure
DH 242 (6)	Apparently sound weld easily obtained, with fine as-cast structure.
GE 1541 (7)	Apparently sound weld easily obtained, with fine grain structure.
Hoskins 875 (8)	Apparently sound weld easily obtained, with fine grain structure.
RA 333 (9)	Apparently sound weld easily obtained, with fine precipitate in a fine grained as-cast structure.
Hastelloy X (10)	Apparently sound weld easily obtained, with a fine acicular as-cast structure.
Udimet 500 (11)	Apparently sound weld easily obtained, with as-cast structure containing fine gamma prime.
Haynes 25 (12)	Apparently sound weld easily obtained, with fine precipitate in as-cast structure.

Electron beam welding schedule range was 30 IPM, 3 ma, 100-130 KV, and 0.025-0.040 circular beam deflection for all specimen joints.

6 CONCLUSIONS

Alloy specification for transpiration cooling material requires selection of an optimum engineering compromise of properties which include oxidation resistance, strength and ductility retention, and manufacturing feasibility. Oxidation and spalling resistance is of paramount importance. The maximum operating temperature and service life of a fine-wire transpiration cooling material are largely determined by the rate of oxidation attack and penetration. Fine wires are more susceptible to damage by oxidation than thicker sheet metal. Uniform oxide penetration of only 0.0003 inch, which may be negligible for a sheet specimen, is substantial for a typical 0.005 inch round wire and results in a 23 percent reduction of cross sectional area and strength. Moreover, some alloys containing small amounts of oxidation inhibiting constituents may be expected to exhibit higher oxidation rates as fine wires because of diffusion geometry. Therefore, oxidation data for sheet metal specimens given in this report should be primarily used for alloy comparison purposes.

Alloy N 155 was chosen as the base-line for comparing other alloys because of its previous use in many types of transpiration cooling materials which have been tested in a variety of applications. The maximum service temperature limit for N 155 is near 1600°F. Other alloys may be compared with base-line N 155 by extrapolating oxidation test data to estimate the temperature at which their oxidation resistance is equal to N 155 at 1600° F. These extrapolations were made for each alloy tested to estimate equivalent temperatures for total oxidation weight gain, spalled oxide weight, and oxidation penetration depth. Data from the average curves shown in Appendixes 2 and 4 at 600 hours exposure time were plotted against reciprocal absolute temperature. These Arrhenius plots, shown in Figures 6-1 to 6-3, indicate comparative oxidation kinetics and provide a basis for temperature extrapolation. The extrapolation results summarized in Table 6-1 are based on N 155 at 1600°F and 600 hours for which total weight gain was 2.4 mg/in^2, spall weight was 5.0 mg/in^2, and oxidation penetration was 0.0003 inch. Equivalent temperatures to produce the same oxidation effects at 600 hours are listed for each alloy.

These extrapolations provide a numerical basis for comparing alloy performance. The data plots summarized in Figures 6-1 to 6-3 showed that the effect of temperature on oxidation rate could be reasonably approximated by either a straight line or a upward-concave smooth curve having one relatively straight segment. Data fitting the former model indicate a simple exponential temperature-rate relationship while curved plots imply a temperature dependent change in oxidation activation energy. Weight gain, spall weight, and oxidation penetration are all related to oxidation rate but each characteristic is modified by particular alloy properties. The more oxidation resistant alloys (when compared to base-line N 155 at 1600°F) have higher equivalent temperatures but different temperatures for each oxidation characteristic. Moreover, equivalent temperature ranking of the alloys may change somewhat if different comparison temperatures, times, or alloys are chosen, but the general sense of comparison remains constant.

TABLE 6-1
COMPARISON OF EXTRAPOLATED ALLOY PROPERTIES

Alloy		Equivalent Performance Temperature, °F		
		Weight Gain	Spall Weight	Oxidation Penetration
1.	N 155 (base-line) . .	1600	1600	1600
2.	TD nickel	1310	1460	1370
3.	TD nickel-chromium .	1790	2240	2070
4.	Bendel 65-35	1630	1560	1480
5.	Chromel A	1670	1640	1590
6.	DH 242	1650	1650	1620
7.	GE 1541	1720	2180	2020
8.	Hoskins 875	1770	2130	1860
9.	RA 333	1460	1610	1560
10.	Hastelloy X	1510	1820	1640
11.	Udimet 500	1420	1680	1650
12.	Haynes 25	1520	1790	1670

TD nickel-chromium (3) is consistently among the best alloys tested for total oxidation resistance, least spalling, and minimum penetration. This superiority is especially pronounced at the longer exposure times and higher temperatures which are of interest for further transpiration cooling development. Initial strength at room temperature is fairly high and ductility retention is excellent. Elongation is nearly constant at about 20 percent regardless of exposure time or temperature. Electron beam weldability is marginal. A good mechanical joint can be made but the dispersed thoria is agglomerated in the weld zone. This lack of dispersion may result in lowered high temperature strength, but the resultant solid weld may still be stronger than the porous transpiration cooling material. Wire drawing is difficult because of the thoria dispersion and typical inclusions or voids in the "break-down" rod stock. Otherwise, manufacturing and fabrication are expected to be relatively straight-forward. TD nickel-chromium offers excellent potential for further development.

DH 242 (6) is a simple solid-solution nickel-chromium alloy with added columbium to improve ductility retention. Oxidation and spall resistance is surpassed only by TD nickel-chromium and the iron-chromium-aluminum alloys. Mechanical properties, especially elongation, are retained after heat exposure with little degradation, although initial strength is comparatively low. Electron beam welded joints are sound and easily made. DH 242 is easily and inexpensively drawn into wire. Transpiration cooling materials have already been manufactured from this alloy on a production basis, and components, such as turbine blades and shroud liners, have been fabricated by electron beam welding. DH 242 should continue to be useful in these applications.

Hastelloy X (10) proved to be the most oxidation and spall resistant of the conventional superalloys, particularly at the higher temperatures. Strength is fairly high compared to the simpler nickel-chromium alloys and ductility retention is good except at the lowest temperatures of 1400 and 1600°F where over-aging apparently occurs. Electron beam weldability is good. Hastelloy X can be drawn into fine wire at moderate cost and can be made into useful porous wire structures. Sintering is not difficult but requires good temperature control to avoid alloy segregation. Hastelloy X has been used to manufacture a variety of transpiration cooled components, and is probably more useful in comparatively coarse or thick-section constructions which require high strength rather than oxidation resistance.

GE 1541 (7) was not tested at 2100 and 2200°F because similar alloy Hoskins 875 (8) appeared to have greater oxidation resistance at 2000°F. Subsequent tensile testing and metallographic examination showed that alloy 7 offered a better balance of oxidation resistance and mechanical properties than alloy 8. Alloy 7 retained good ductility and strength up to 2000°F while alloy 8 became comparatively brittle. Alloy 7 is exceeded only by TD nickel-chromium in combined oxidation resistance and stability of mechanical properties after heating. Electron beam weldability appears to be good. Manufacturing feasibility is complicated because GE 1541 is not yet widely available, especially in wire form, and present sintering practices cannot be employed. The necessary aluminum and yttrium content of alloy 7 requires special surface cleaning procedures and vacuum sintering or gettering techniques instead of usual dry-hydrogen atmosphere sintering. In spite of these problems, GE 1541 offers excellent potential for further development as a transpiration cooling material alloy.

Other alloys which were tested were considered to be less suitable for transpiration cooling materials. Hoskins 875 (8) has excellent oxidation resistance but comparative ductility retention is low. Bendel 65-35 (4) and Chromel A (5) had good oxidation resistance but were generally surpassed by the similar alloys TD nickel-chromium and DH 242. Udimet 500 (11) and Haynes 25 (12) had fair oxidation resistance. However, the former is difficult to sinter because of its aluminum and titanium content and the latter is surpassed by Hastelloy X in these tests. Alloys TD nickel (2), N 155 (1), and RA 333 (9) were least oxidation resistant in the order given.

Based on these sheet specimen screening tests, the major conclusions of this report are summarized.

1. TD nickel-chromium, DH 242 nickel-chromium, and Hastelloy X alloys were chosen for further testing as 0.005 inch diameter wires.

2. GE 1541 alloy, in retrospect, should have been chosen for testing at 2100 and 2200°F and further testing in wire form.

3. TD nickel-chromium alloy was the most oxidation resistant and mechanically stable alloy tested. In spite of marginal electron beam weldability, further investigation and development is recommended.

4. DH 242 nickel-chromium alloy had very good oxidation resistance, ductility retention, and electron beam weldability which support its continued use in transpiration cooling materials.

5. Hastelloy X alloy was most oxidation resistant of the conventional superalloys tested, and demonstrated good strength, ductility retention, and weldability.

6. GE 1541 alloy had excellent oxidation resistance, ductility retention and weldability. In spite of probable sintering difficulty, further investigation and development is recommended.

TABLE 3-1 ALLOY ANALYSIS.

Alloy	Refer Below	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb + Ta	Ti	Al	Fe	Cu	S	P	Other
1	1	0.10	1.51	0.73	21.35	20.26	19.93	2.98	2.50	1.02	--	--	Bal	--	0.011	0.020	
N 155	13	0.10	1.76	0.80	21.51	20.16	19.93	2.64	2.25	1.20	--	--	Bal	--	0.012	0.007	
2	2	0.0009	--	--	<0.01	Bal	<0.01	--	--	--	<0.001	--	<0.01	<0.001	0.001	--	2.60 ThO_2
TD nickel	13	0.02	--	--	--	98.64	--	--	--	--	--	--	--	--	0.002	0.006	
3	3	62 PPM	--	--	20.72	Bal	--	--	--	--	--	--	--	--	18 PPM	--	2.60 ThO_2
TD nickel-chromium	13	0.01	--	--	20.61	Bal	--	--	--	--	--	--	--	--	0.029	0.012	
4	4	--	--	--	34.0	63.0	--	--	--	--	--	--	--	--	--	--	3.0 Spinel
Bendel 65-35	13	0.09	0.13	0.81	35.89	61.90	--	--	--	--	--	--	--	--	0.007	0.011	
5	5	--	0.20	1.40	20.0	78.0	--	--	--	--	--	--	--	--	--	--	
Chromel A	13	0.02	0.05	0.74	20.61	78.60	--	--	--	--	--	--	--	--	0.006	0.004	
6	6	0.02	0.08	0.96	19.4	Bal	--	--	--	1.28	--	--	0.96	--	--	--	
DH 242	13	0.04	0.02	1.16	22.28	Bal	--	--	--	1.03	--	--	1.40	--	0.005	0.005	
7	7	--	--	28 PPM	15.36	--	--	--	--	--	--	4.19	Bal	35 PPM	17 PPM	70 PPM	0.43 Y
GE 1541	13	0.01	0.02	0.03	13.64	--	--	--	--	--	--	4.20	Bal	--	0.003	0.004	0.88 Y
8	8	--	--	--	22.35	--	--	--	--	--	--	5.80	Bal	--	--	--	
Hoskins 875	13	0.03	0.25	0.91	22.25	--	--	--	--	--	--	5.39	Bal	--	0.005	0.005	
9	9	0.03	1.34	0.94	25.80	46.87	2.81	2.80	2.93	--	--	--	Bal	0.03	0.008	0.012	
RA 333	13	0.07	1.20	0.82	24.89	46.08	3.05	2.60	3.72	--	--	--	Bal	--	0.023	0.011	
10	10	0.015	0.57	0.84	22.47	Bal	0.93	9.12	0.57	--	--	--	18.35	--	0.007	0.018	
Hastelloy X	13	0.13	0.57	0.78	21.54	Bal	1.64	8.52	0.73	--	--	--	19.81	--	0.006	0.006	
11	11	0.07	<0.1	<0.1	18.9	Bal	19.1	4.05	--	--	3.01	3.00	0.18	<0.1	0.003	--	
Udimet 500	13	0.07	0.05	0.04	19.06	Bal	19.40	4.30	--	--	3.05	3.17	0.01	--	0.005	0.003	
12	12	0.11	1.45	0.16	19.81	10.04	Bal	--	14.61	--	--	--	1.80	--	0.008	0.023	
Haynes 25	13	0.10	1.25	0.18	19.89	10.32	Bal	--	15.78	--	--	--	2.03	--	0.015	0.004	

Alloy Suppliers	Mill Certification	Heat No.
1. Union Carbide Corporation	AMS 5532 B	M5 - 5490
2. E. I. duPont de Nemours & Company	Proprietary Alloy	1114
3. Same as 2	Proprietary Alloy	Not Specified
4. The Bendix Corporation	Proprietary Alloy	Not Specified
5. Hoskins Manufacturing Company	AMS 5676	2159
6. Driver-Harris Company	Proprietary Alloy	Not Specified
7. General Electric Company	Proprietary Alloy	MS - 43
8. Same as 5	Proprietary Alloy	4327
9. Rolled Alloys, Incorporated	MS 5593	3551
10. Same as 1	AMS 5536 C	X4 - 4598
11. Special Metals Corporation	AMS 5753	6 - 3838
12. Same as 1	AMS 5537 B	L5 - 1734

Independent Chemical Analysis

13. Arco Spectro-Chemical Laboratory

TABLE 4-1 METALLOGRAPHIC ETCHANT SCHEDULE.

ALLOY	ETCHANT	PROCEDURE
1 N 155	2% Chromic acid - 4 ml Hydrochloric acid - 96 ml	Let solution set for one-half hour or until solution lightens. Using a carbon cathode electrolytic etch with 5 volts until a blue stain appears. Turn the current off and swirl the sample in the etchant until the blue stain is removed.
2 TD nickel	Ferric chloride - 5 gm Hydrochloric acid - 50 ml Water - 100 ml	Swab.
3 TD nickel-chromium	10% Oxalic acid	Electrolytic: 5 volts, 3-10 seconds.
4 Bendel 65-35	Hydrochloric acid - 1 part Glycerol - 1 part	Swab with solution; use heat lamp to heat specimen to start etching reaction.
5 Chromel A	Hydrochloric acid - 1 part Glycerol - 1 part	Same as Alloy 4 (Bendel 65-35).
	ALTERNATE ETCHANT 2% Chromic acid - 4 ml Hydrochloric acid - 96 ml	Same as Alloy 1 (N 155).
6 DH 242	10% Oxalic acid	Electrolytic: 5 volts, 5-25 seconds.
7 GE 1541	10% Oxalic acid	Electrolytic: 5 volts, 15-60 seconds.
8 Hoskins 875	10% Oxalic acid	Electrolytic: 5 volts, 20-60 seconds.
9 RA 333	10% Oxalic acid	Electrolytic: 5 volts, 3-10 seconds.
10 Hastelloy X	Ferric chloride - 5 gm Hydrochloric acid - 50 ml Water - 100 ml	Swab.
	ALTERNATE ETCHANT 10% Oxalic acid	Electrolytic: 5 volts, 2-5 seconds.
11 Udimet 500	Ferric chloride - 5 gm Hydrochloric acid - 50 ml Water - 100 ml	Swab.
	ALTERNATE ETCHANT 10% Oxalic acid	Electrolytic: 5 volts, 2-6 seconds.
12 Haynes 25	2% Chromic acid - 4 ml Hydrochloric acid - 96 ml	Same as Alloy 1 (N 155).

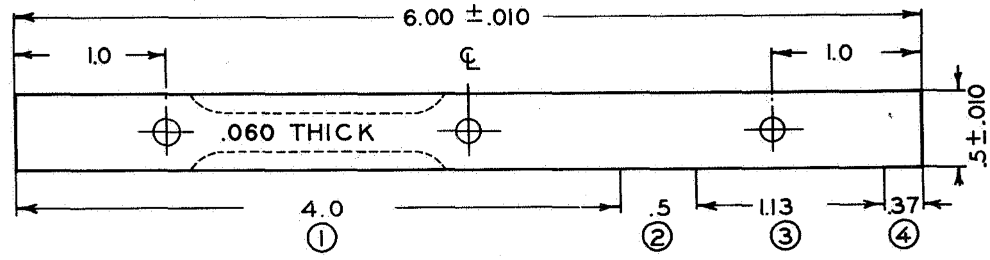
TABLE 5.5-1 MECHANICAL PROPERTIES.

Alloy Number	As Received				As Sintered				Electron Beam Welded		
	Yield Strength 10^3 psi	Ultimate Strength 10^3 psi	Elongation Percentage One Inch	Hardness	Yield Strength 10^3 psi	Ultimate Strength 10^3 psi	Elongation Percentage One Inch	Hardness	Yield Strength 10^3 psi	Ultimate Strength 10^3 psi	Elongation Percentage One Inch
1	59.6	115.3	50	91 R_B	36.6	96.5	51	77 R_B	39.1	101.0	59
2	56.5	67.9	17	87 R_B	43.1	66.9	18	82 R_B	36.1	42.3[1]	30
3	93.5	136.6	20	30 R_C	93.0	137.0	18	31 R_C	85.3	85.3[1]	1
4	—	—	—	—	—	—	—	87 R_B	52.7	72.0[1]	6
5	41.3	107.2	39	82 R_B	30.4	94.0	40	70 R_B	30.6	92.8	39
6	42.5	110.1	41	81 R_B	32.0	97.5	47	72 R_B	28.6	80.4	35
7	83.6	87.5	9	99 R_B	51.3	73.5	25	85 R_B	38.9	54.4[1]	3
8	82.6	115.2	25	101 R_B	62.5	62.5	1	96 R_B	27.0	27.0	2
9	63.6	112.2	43	89 R_B	38.5	93.0	56	74 R_B	35.0	81.8	48
10	63.6	116.4	39	95 R_B	40.3	80.2	19	82 R_B	40.7	83.5	22
11	156.4	213.0	11	45 R_C	94.8	156.5	22	29 R_C	94.0	145.1[1]	20
12	71.6	142.2	48	97 R_B	56.4	114.8	37	90 R_B	56.3	108.1	36

[1]Broke at weld

SPECIMEN AND EQUIPMENT SCHEMATICS

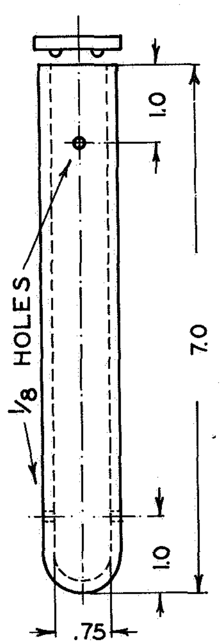
TEST SPECIMEN COUPON



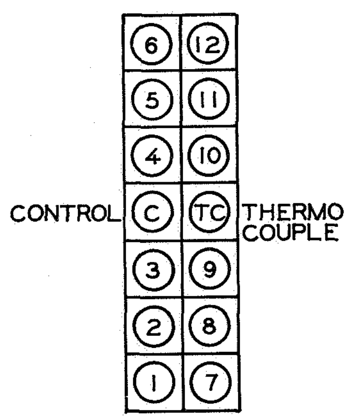
TEST SEGMENTS

① TENSILE TEST SPECIMEN ASTM E-8 ½ SIZE
② NASA-LEWIS EXAMINATION SPECIMEN
③ MACROSCOPIC EXAMINATION SPECIMEN
④ METALLOGRAPHIC EXAMINATION SPECIMEN
⌖ MICROMETER MEASUREMENT POINTS

ZIRCON THIMBLE



SPECIMEN RACK ARRANGEMENT



ALLOY COUPONS

SPECIMEN PAN FURNACE LOAD

600	SPARE
400	500
200	300
64	100
4	16

RACKS BY TIME OF PULL HOURS

Figure 4.1 Specimen and test schematic.

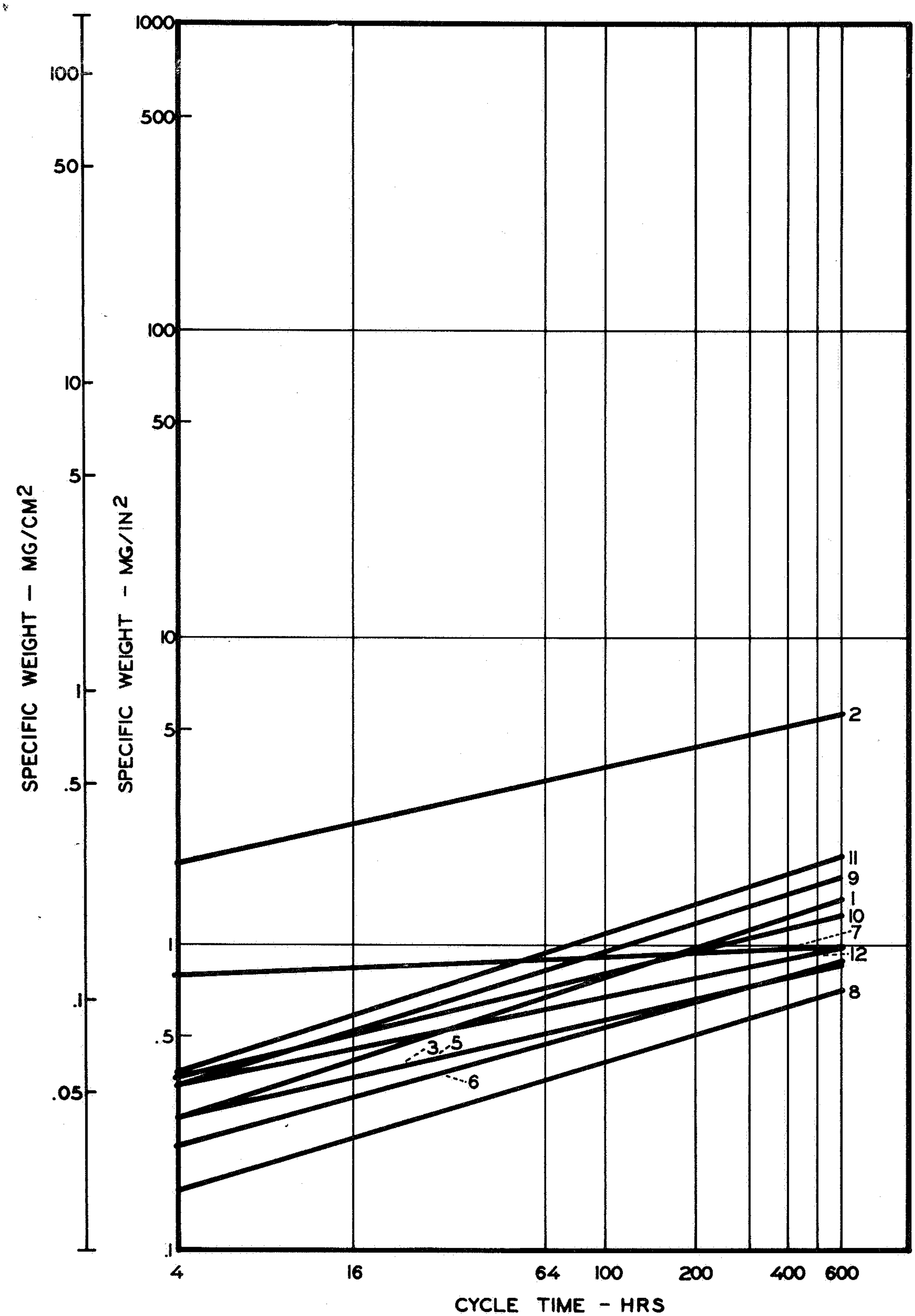


Figure 5.1-1 Oxidation resistance comparison, 1400°F.

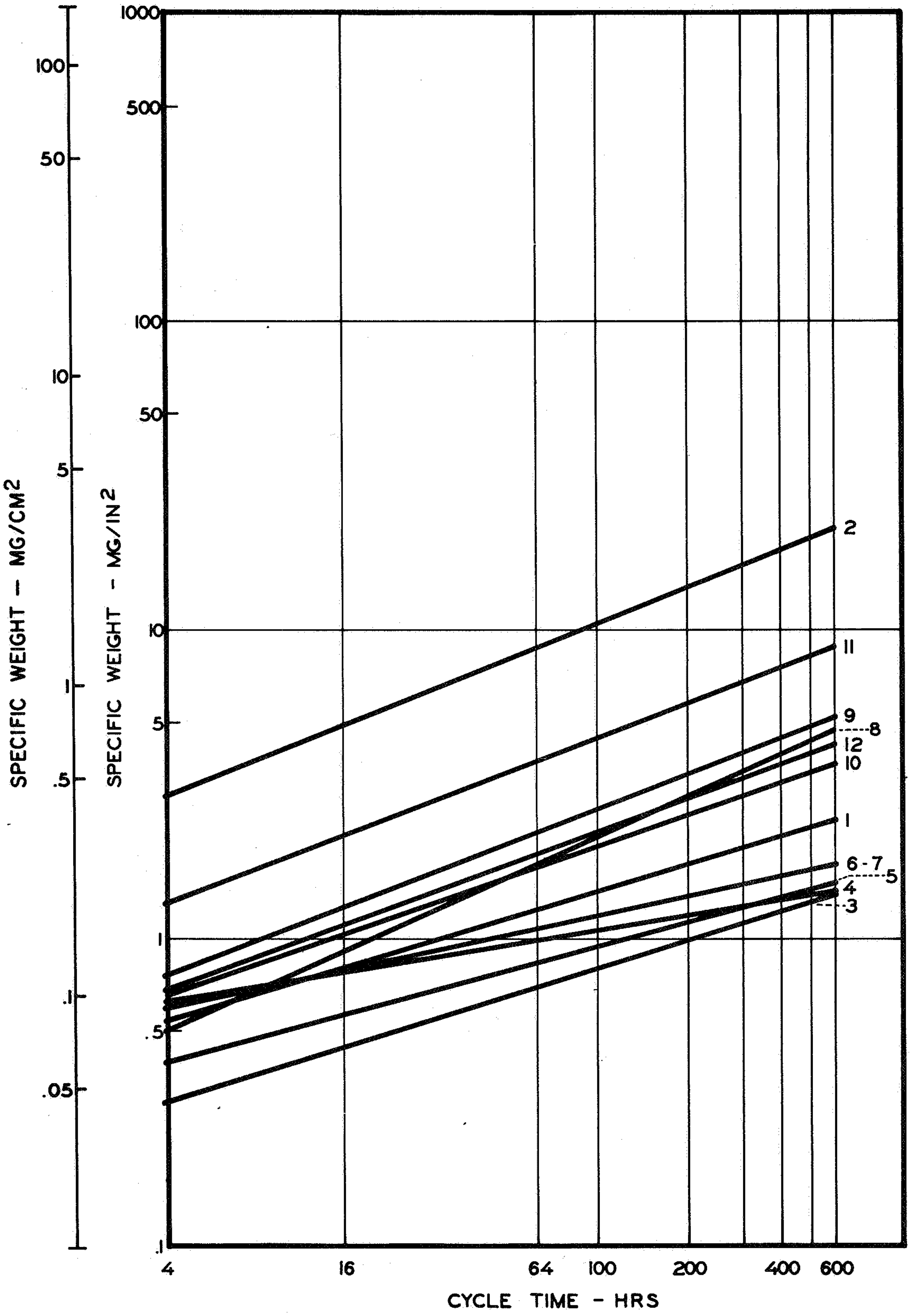


Figure 5.1-2 Oxidation resistance comparison, 1600°F.

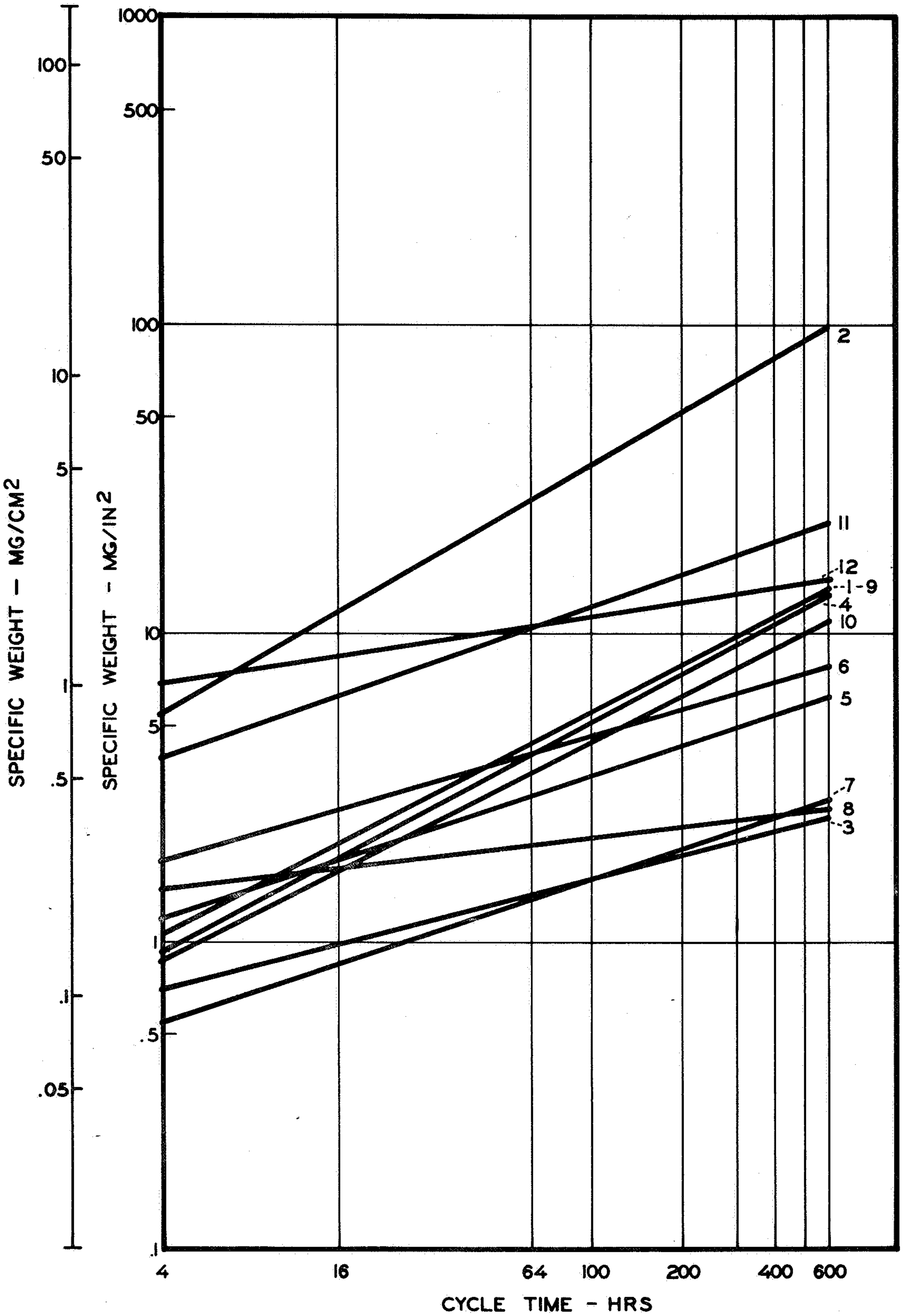


Figure 5.1-3 Oxidation resistance comparison, 1800°F.

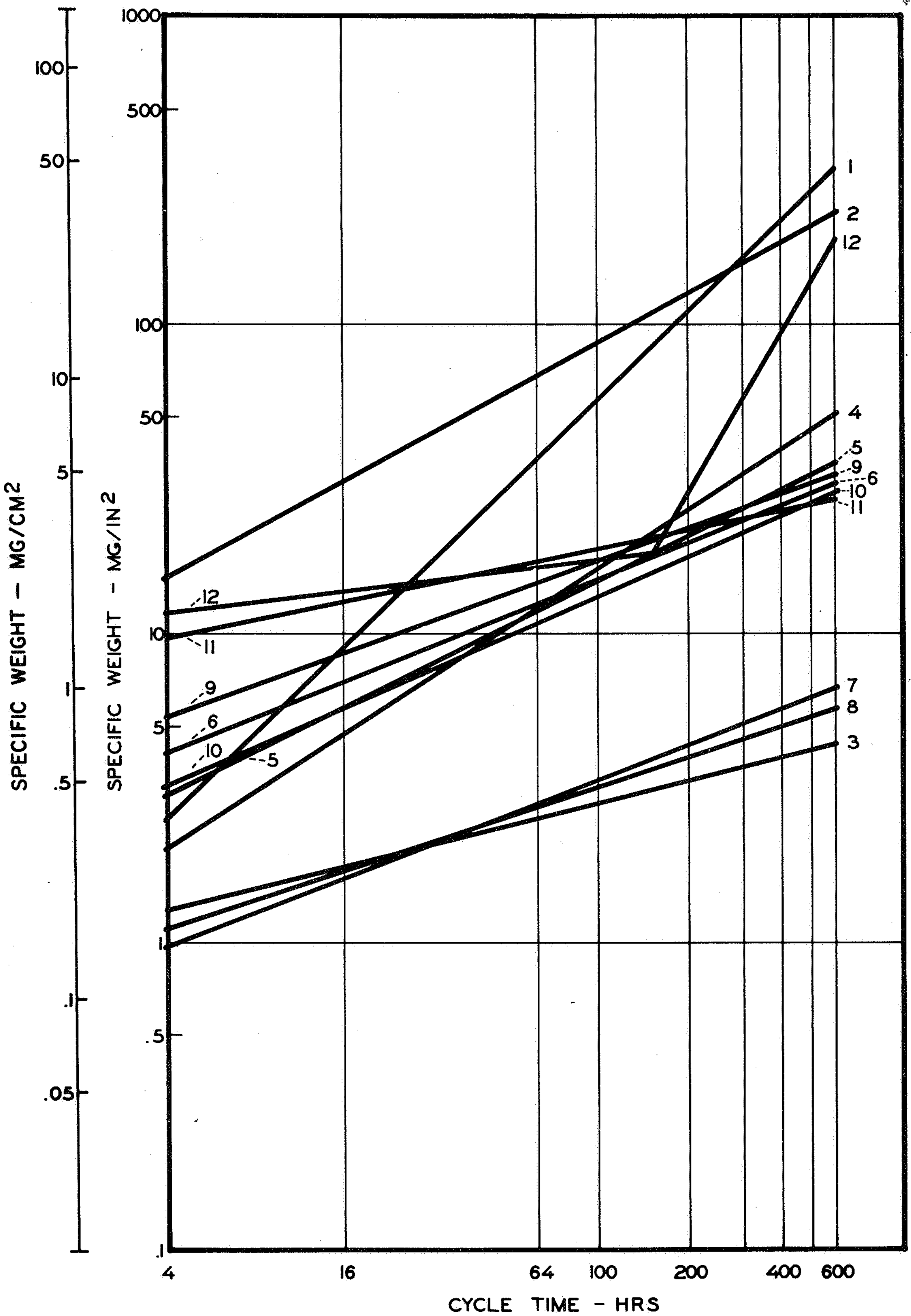


Figure 5.1-4 Oxidation resistance comparison, 2000°F.

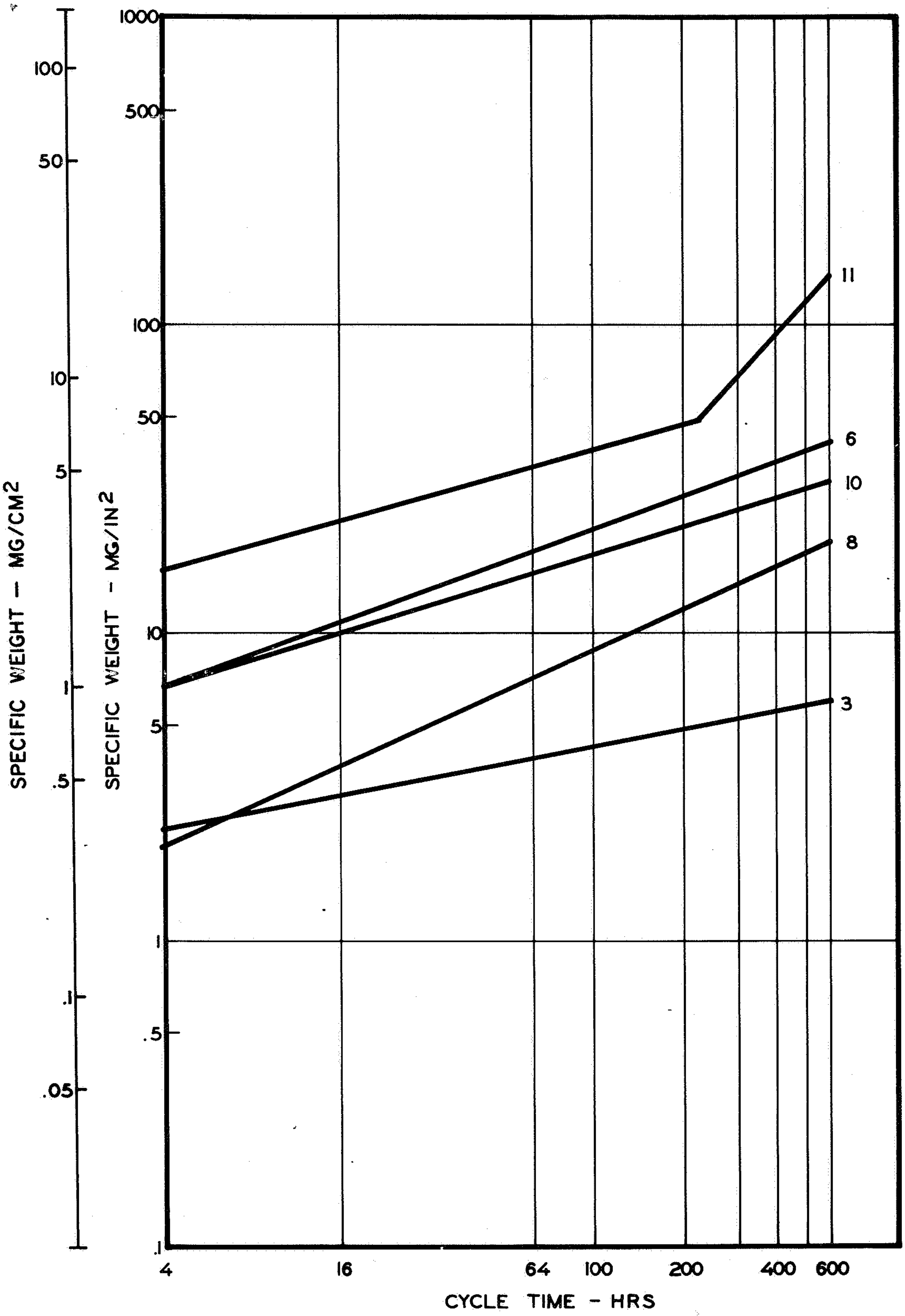


Figure 5.1-5 Oxidation resistance comparison, 2100°F.

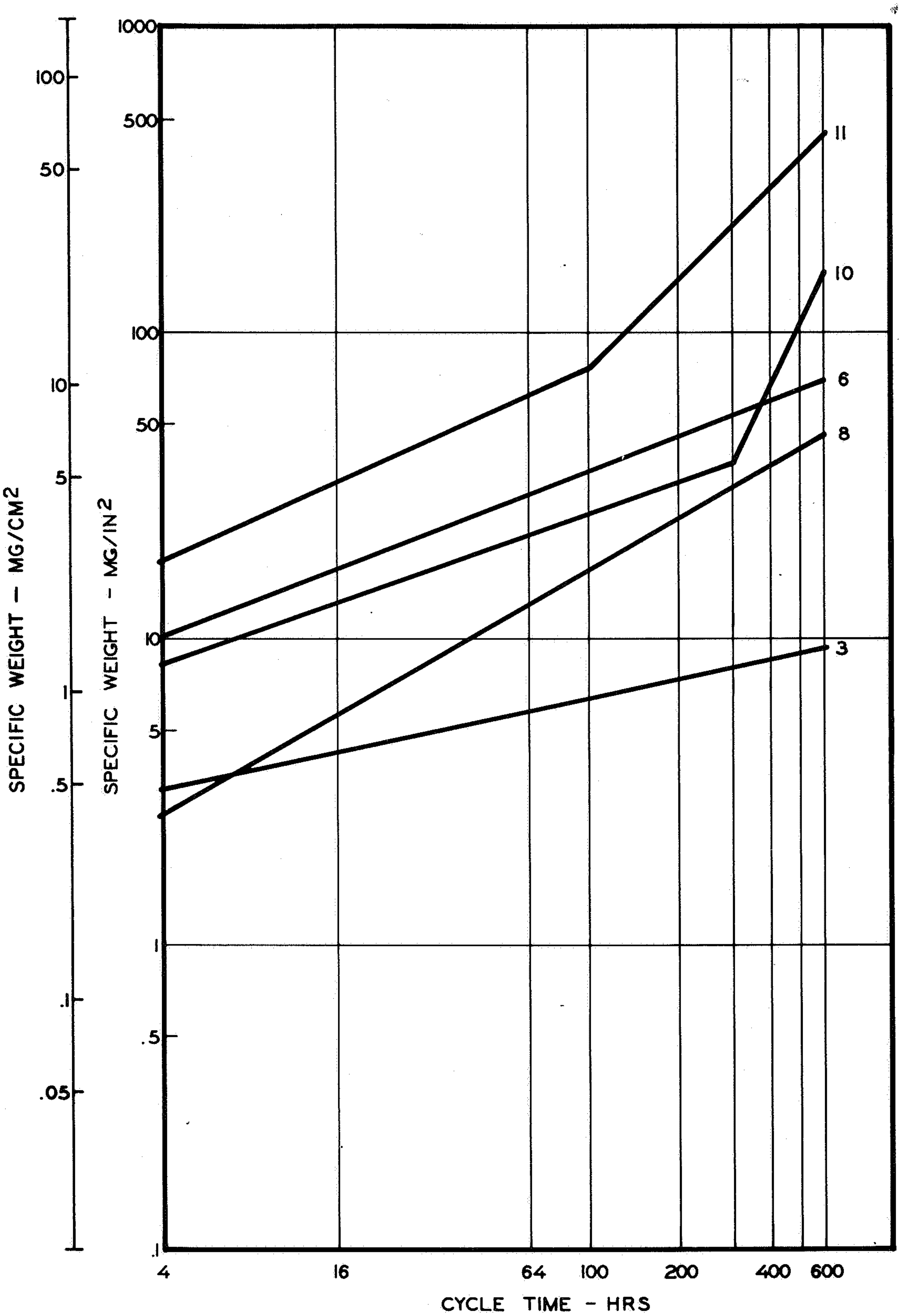


Figure 5.1-6 Oxidation resistance comparison, 2200°F.

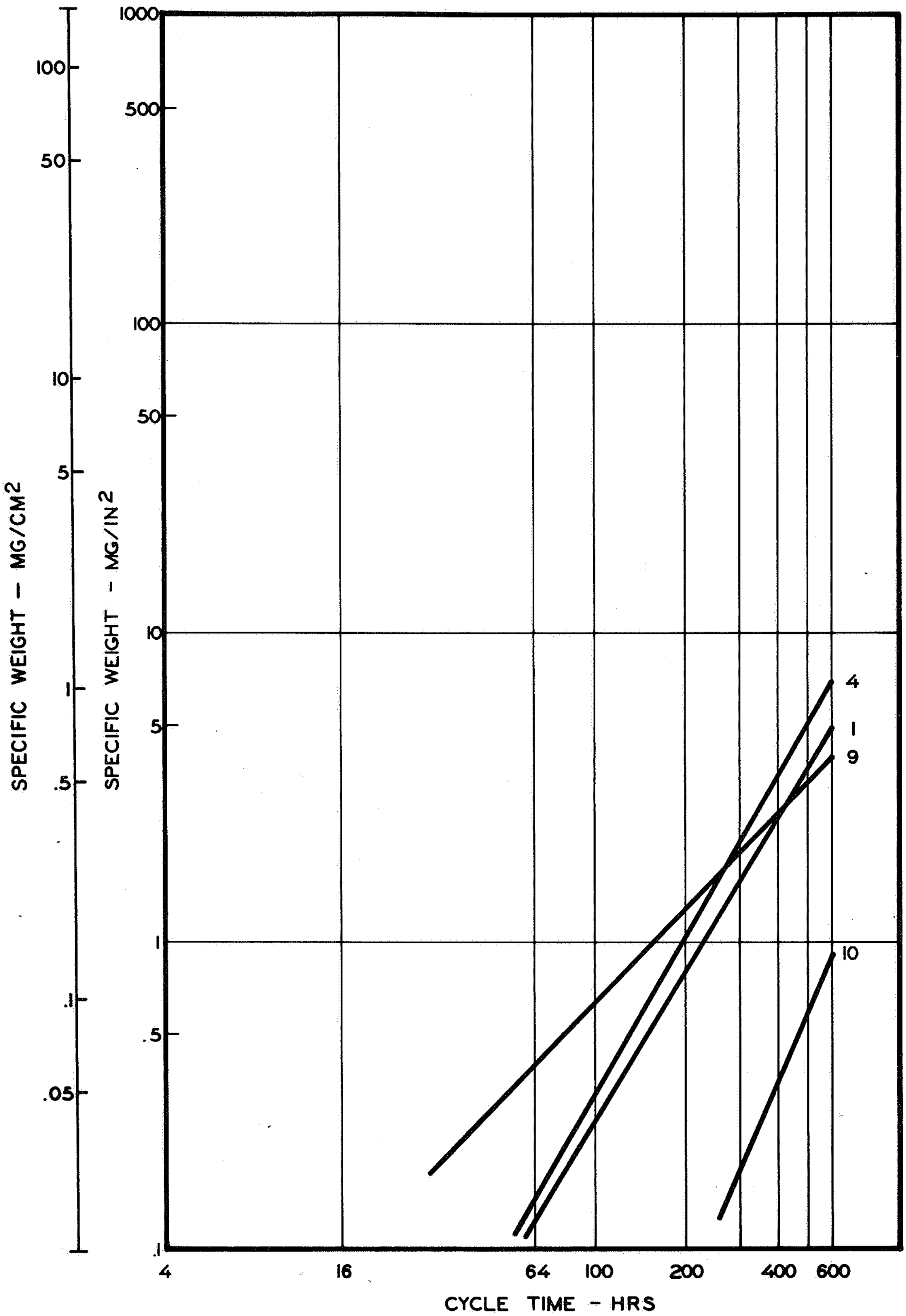


Figure 5.1-7 Spalling resistance comparison, 1600°F.

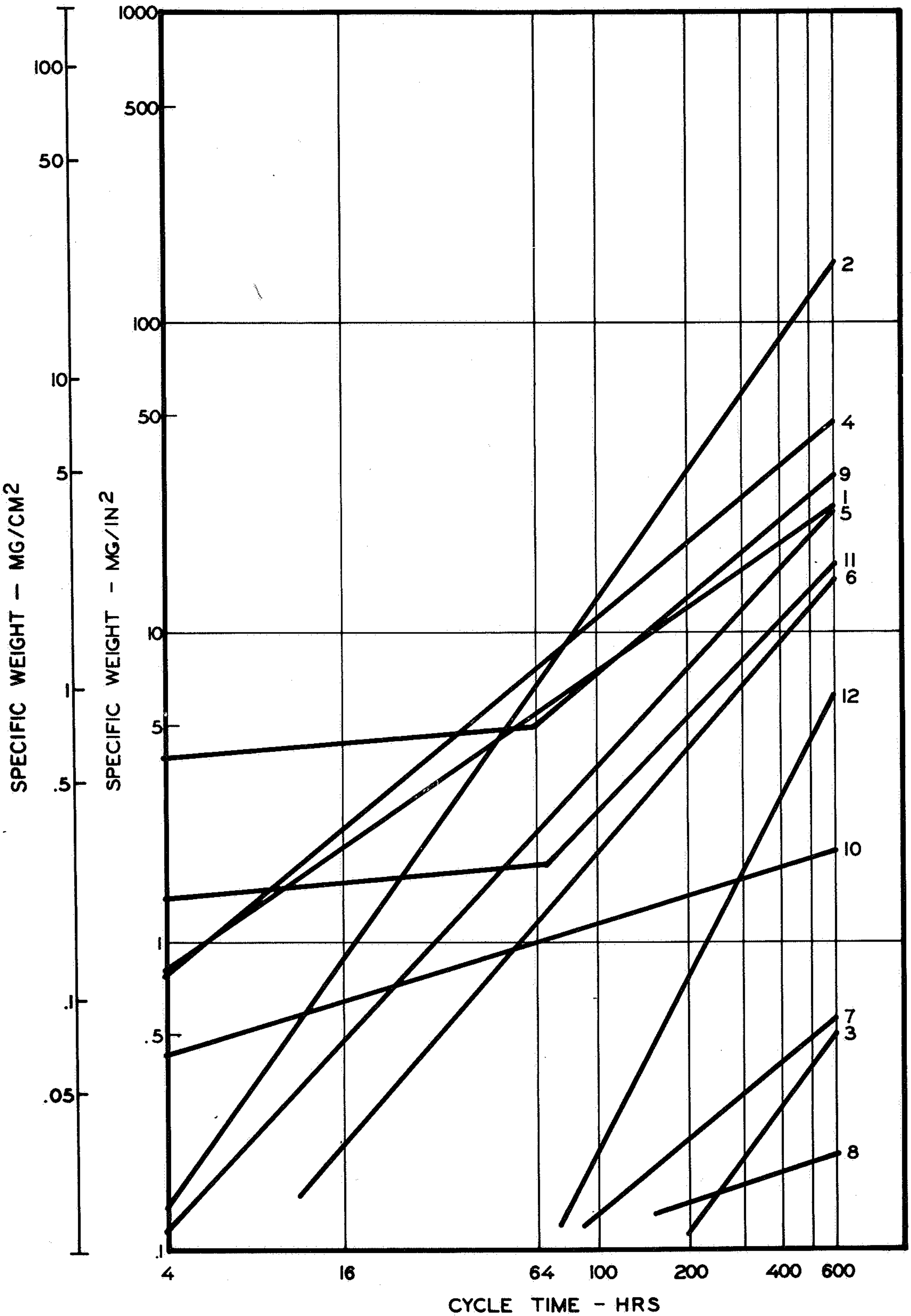


Figure 5.1-8 Spalling resistance comparison, 1800°F.

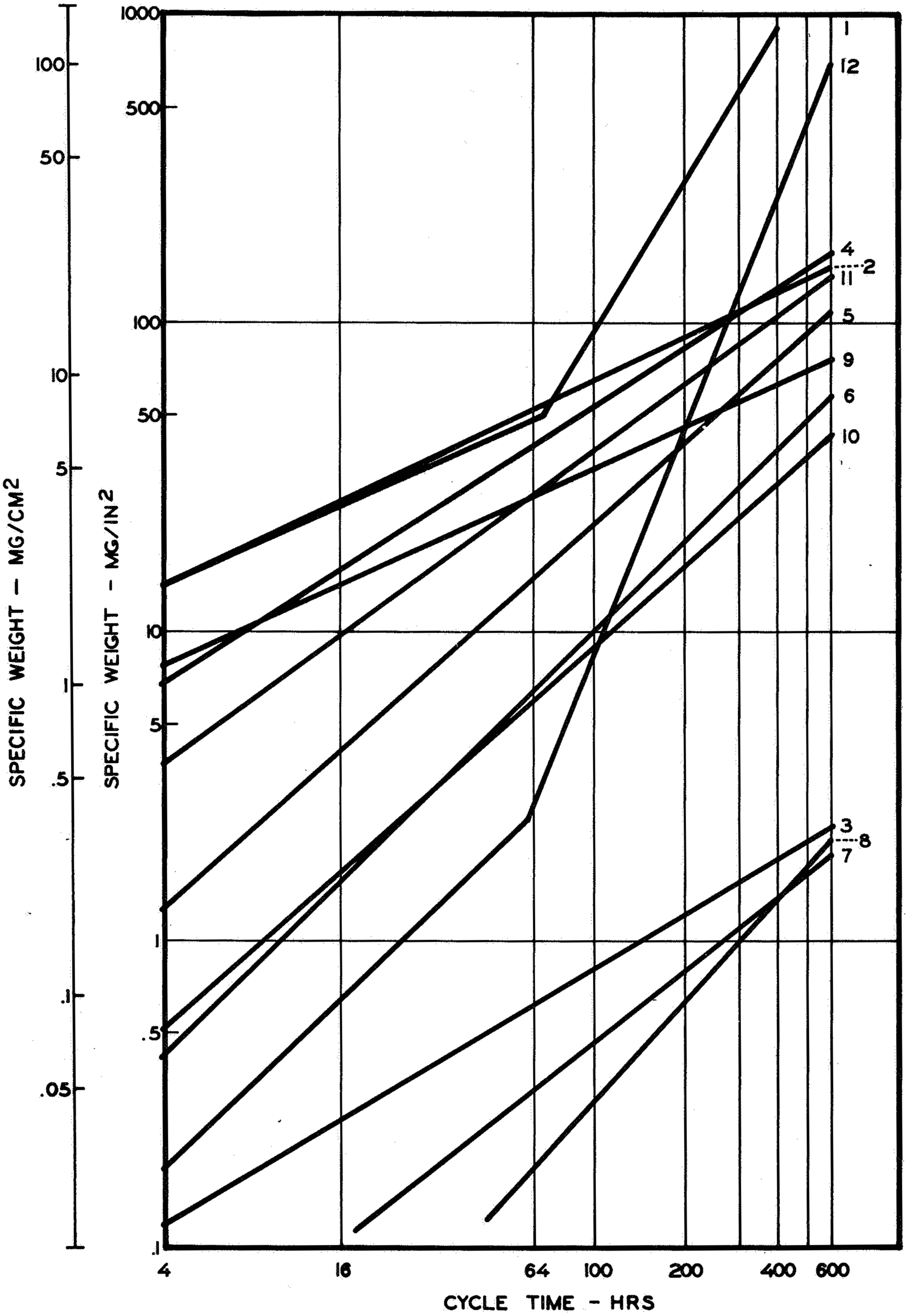


Figure 5.1-9 Spalling resistance comparison, 2000°F.

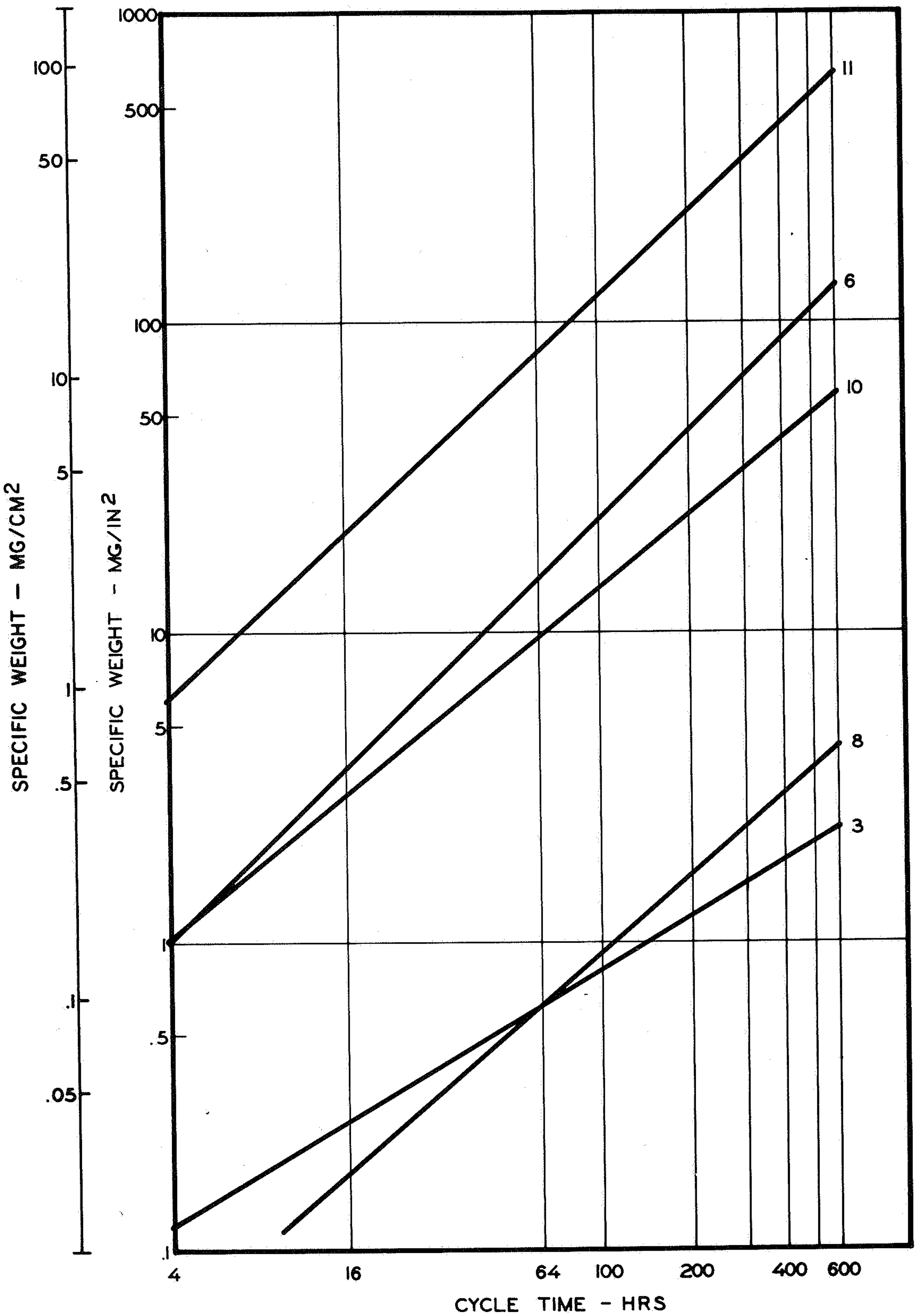


Figure 5.1-10 Spalling resistance comparison, 2100°F.

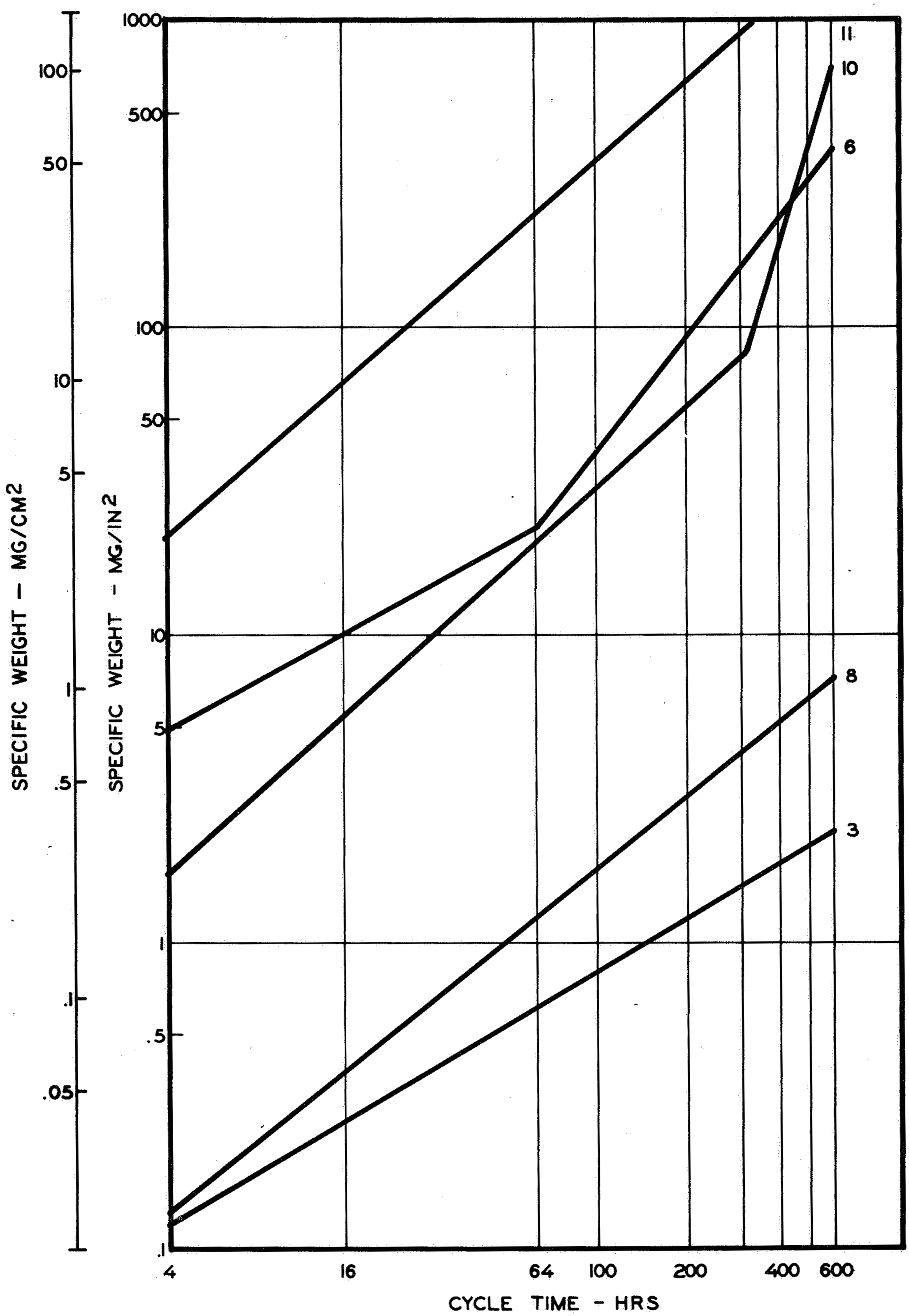


Figure 5.1-11 Spalling resistance comparison, 2200°F.

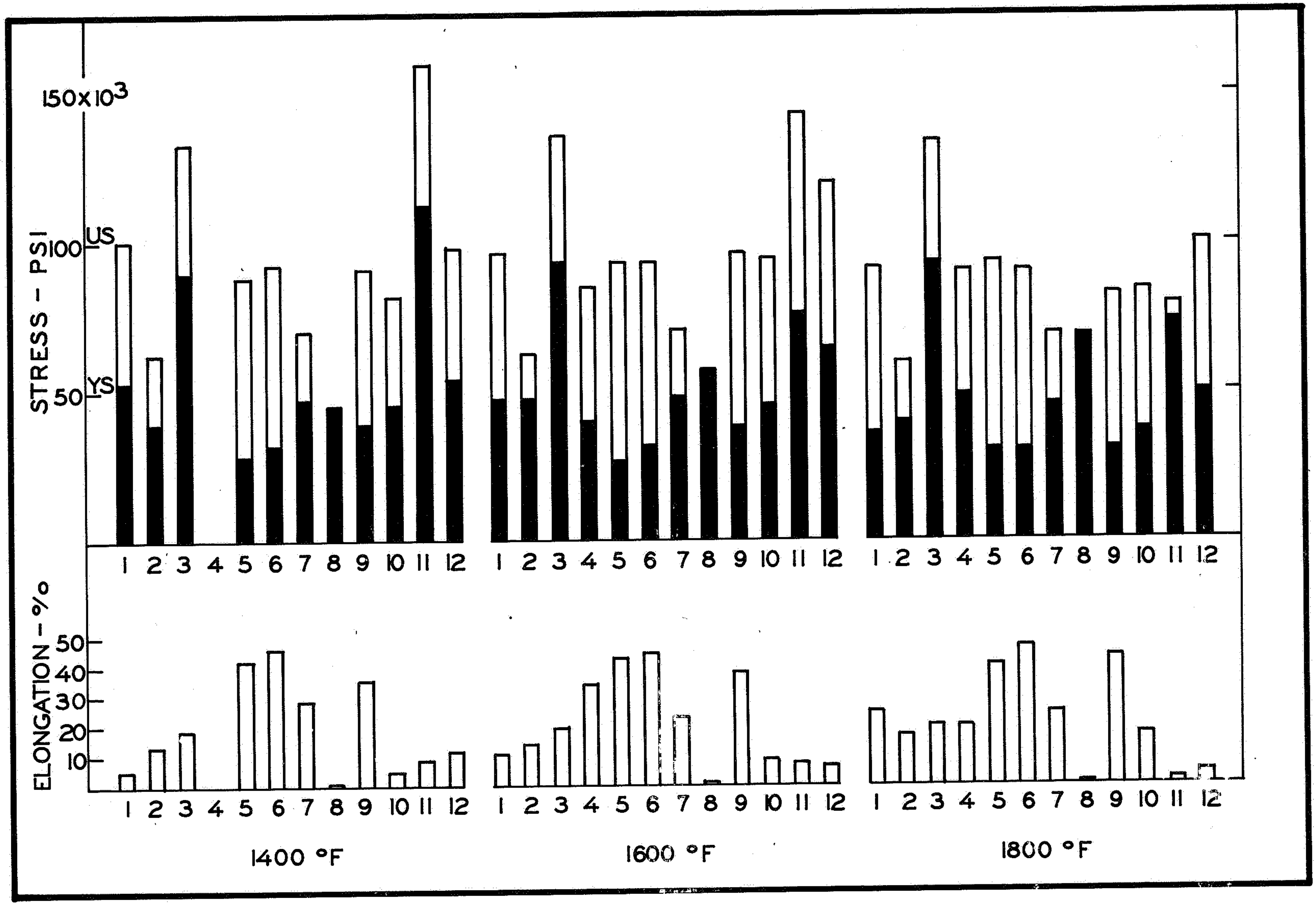


Figure 5.4-1 Mechanical properties comparison, 1400-1800°F.

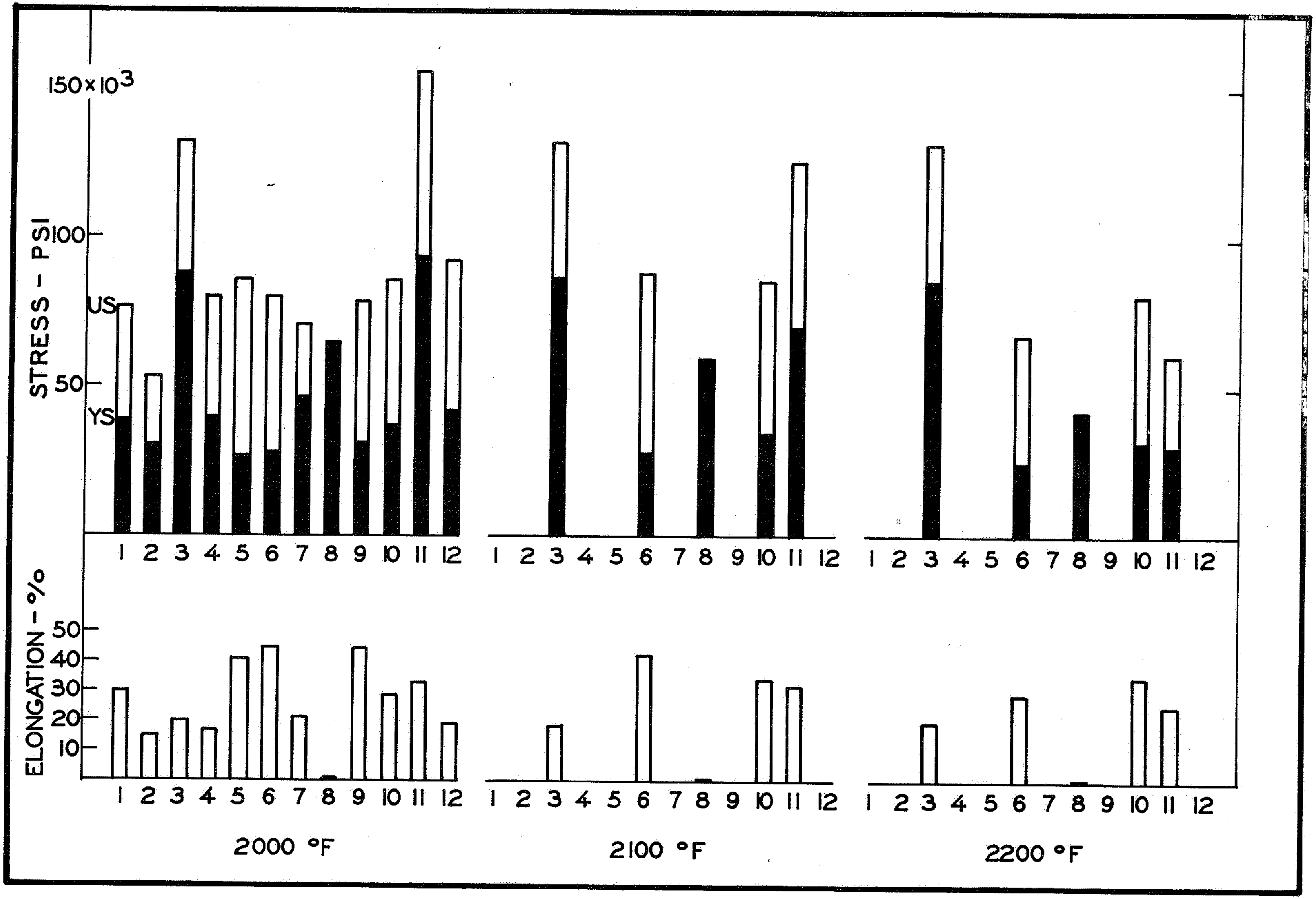


Figure 5.4-2 Mechanical properties comparison, 2000-2200°F.

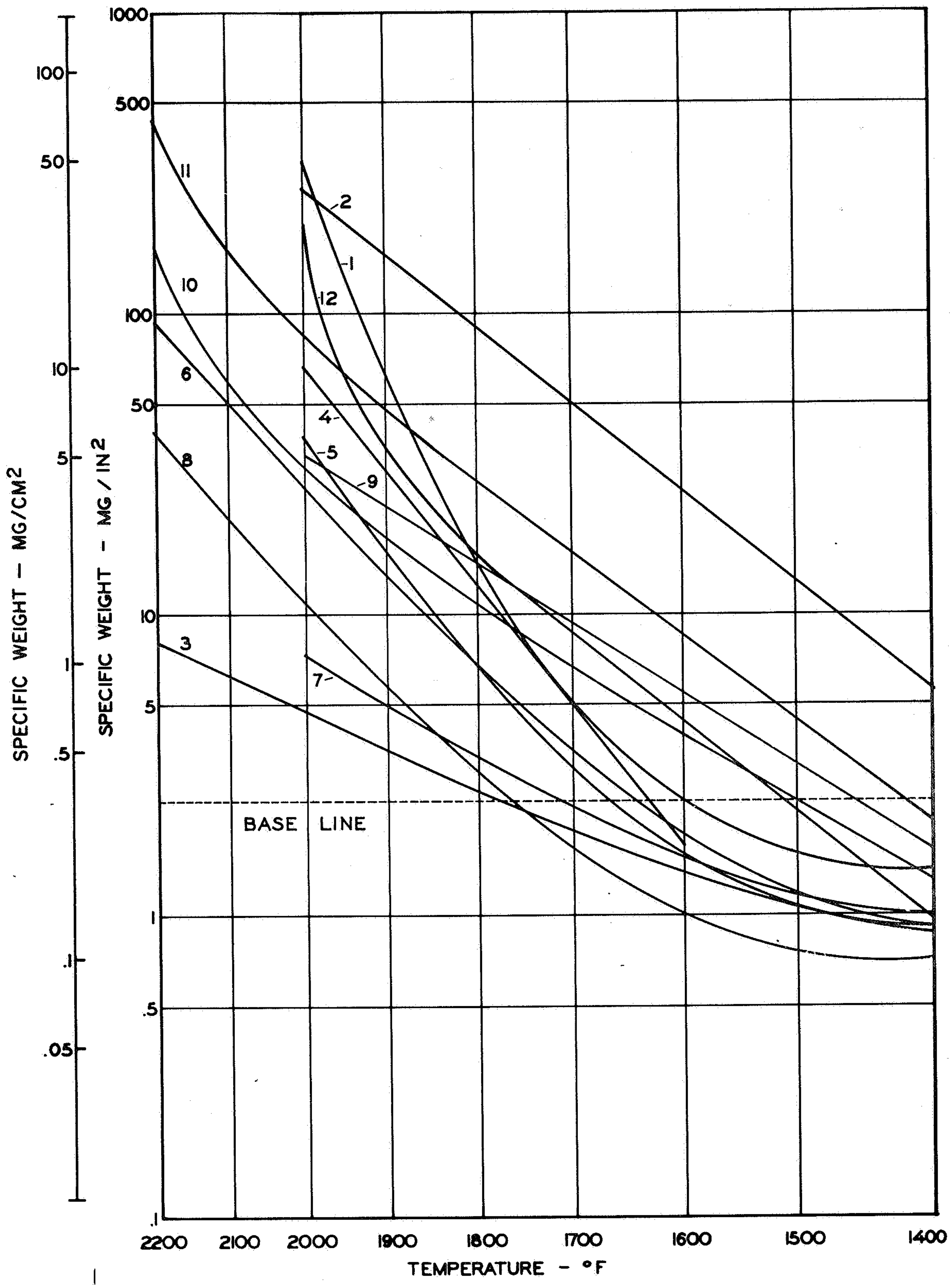


Figure 6-1 Extrapolated oxidation resistance comparison.

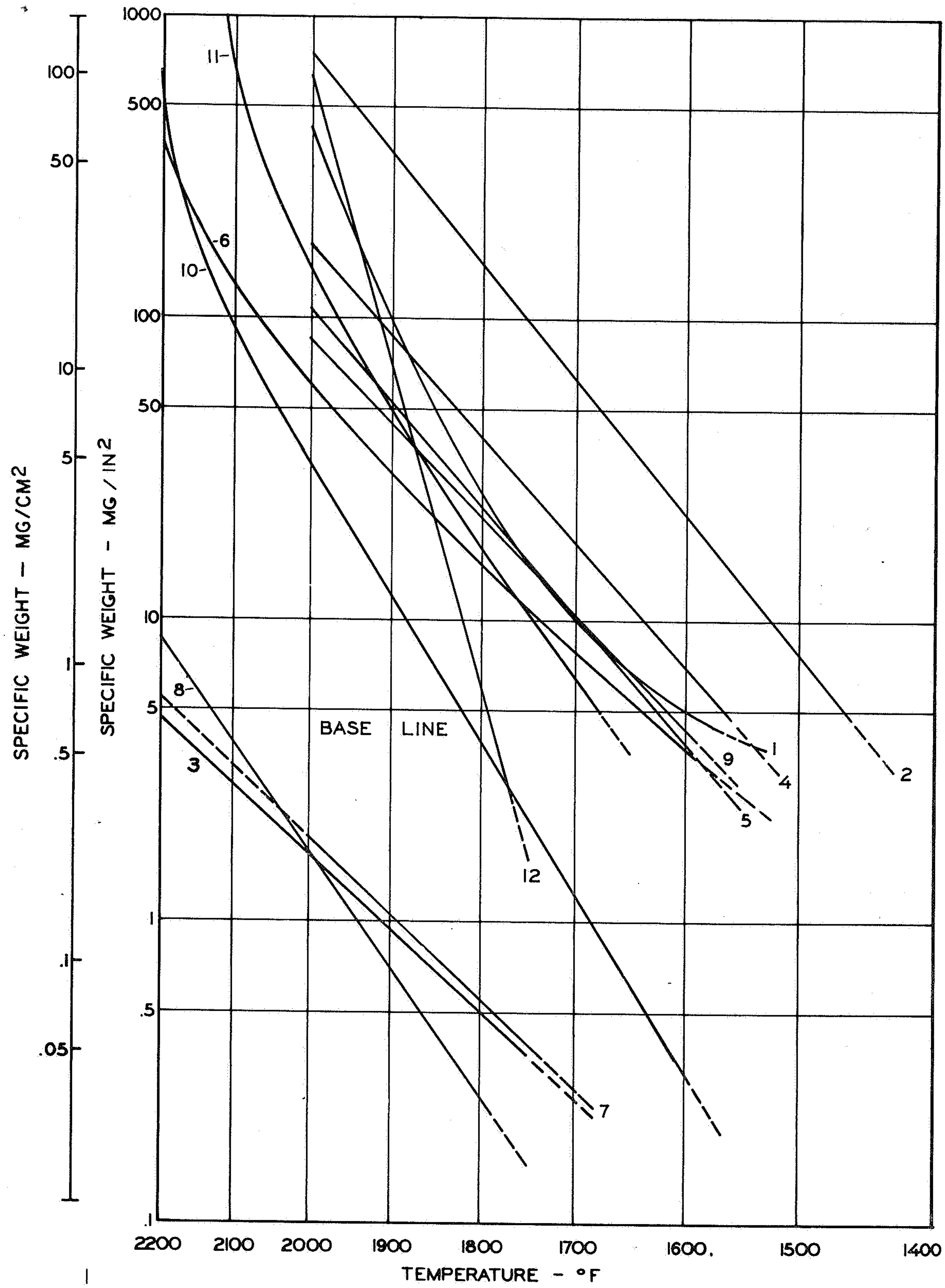


Figure 6-2 Extrapolated spalling resistance comparison.

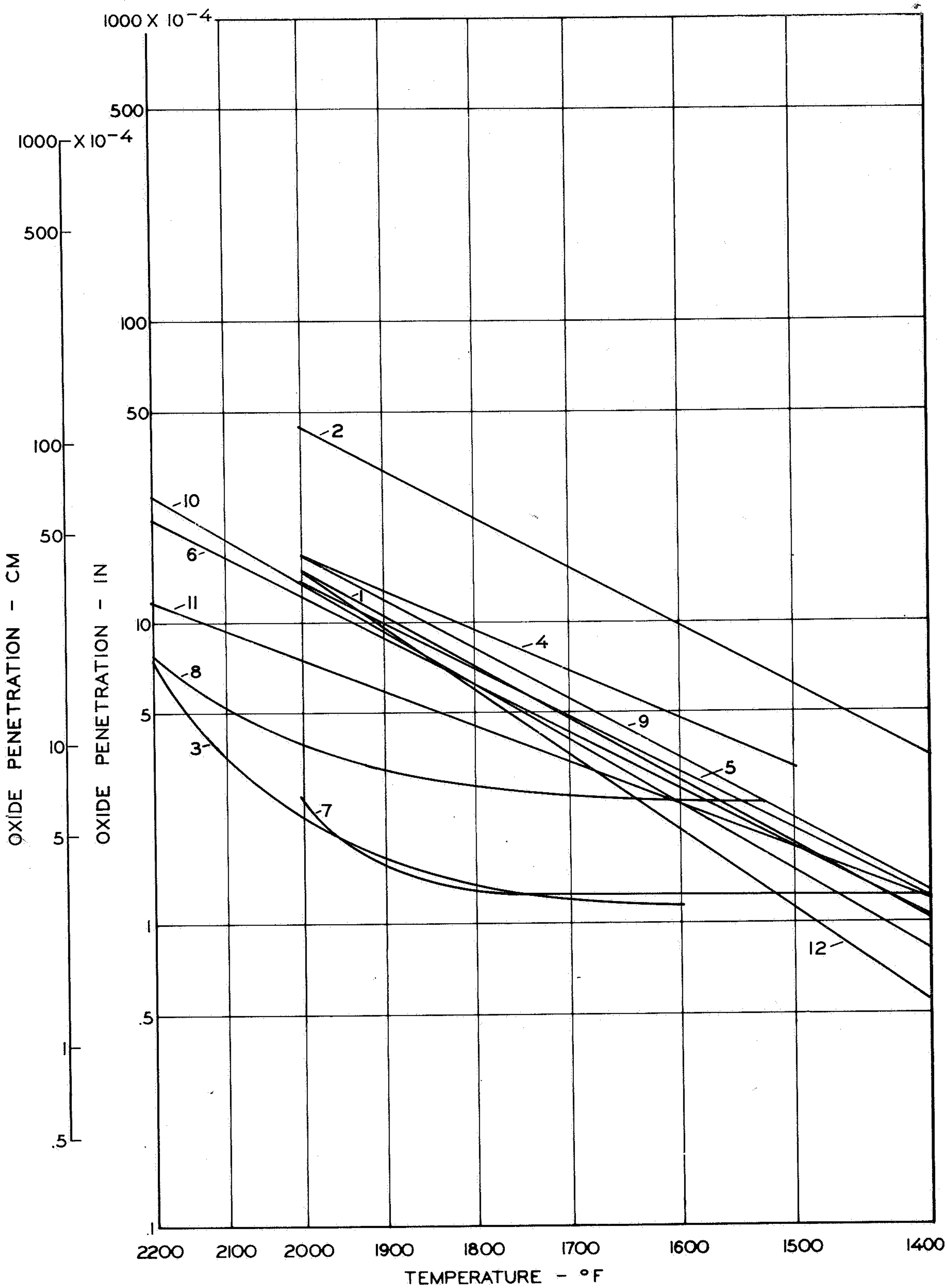


Figure 6-3 Extrapolated penetration resistance comparison.

APPENDIX 1
NUMERICAL DATA TABULATION

CONTENTS

ALLOY	TABLE	PAGE
1. N 155	A1-1	44
2. TD nickel	A1-2	46
3. TD nickel-chromium	A1-3	48
4. Bendel 65-35	A1-4	50
5. Chromel A	A1-5	52
6. DH 242	A1-6	54
7. GE 1541	A1-7	56
8. Hoskins 875	A1-8	58
9. RA 333	A1-9	60
10. Hastelloy X	A1-10	62
11. Udimet 500	A1-11	64
12. Haynes 25	A1-12	66

Reduced numerical data is given for each alloy tested according to the following legend:

A	Exposure Time (hours)	All times are total hours at the specified temperature. Samples were allowed to air cool to room temperature between cycles.
B	Specific total weight gain direct method (mg/in^2)	The specimen was weighed before and after exposure. The difference plus the spall divided by original sample area was designated specific total weight gain — direct method. At low temperatures or where the amount of spall was small, the direct method was more predictable than the indirect method.
C	Specific total weight gain indirect method (mg/in^2)	The ceramic thimble and the specimen were weighed together before and after exposure. The difference divided by original sample area was designated specific total weight gain — indirect method. At high temperatures or where the amount of spall was large, the indirect method was more predictable than the direct method.
D	Specific spall weight (mg/in^2)	The metal oxide that was collected in the ceramic thimble divided by original sample area was designated specific spall weight.
E	Thickness change, (10^{-3} inches)	Based on the average of three (3) measurements with hand micrometer. Both ends and the center were measured.

F	Average oxide thickness, (10^{-3} inches)	Uniform oxide layer plus depth of average intergranular oxide measured from metallographic sections.
G	Maximum depth of penetration (10^{-3} inches)	Maximum depth of oxide penetration measured from metallographic sections.
H	Yield strength (psi)	Determined using 0.2% offset. Area based on measurements after exposure.
I	Ultimate strength (psi)	Area based on measurements after exposure.
J	Elongation (percent)	Measured on one (1) inch gage length layout.
K	Metal strip (color)	B : Black Bl : Blue Br : Brown G : Gray Gr : Green P : Purple IC : Interference Color L : Light
L	Metal strip (texture)	S : Smooth-metallic P : Powdery F : Flaky L : Laminated M : Melt-like blisters Pt : Pitted
M	Metal strip (magnetic properties)	ND : Not Detectable W : Weak S : Strong
N	Spall (weight)	Total weight (not specific weight). ND : Not detectable 1 : <0.001 grams 2 : 0.001 - 0.01 3 : 0.01 - 0.1 4 : 0.1 - 1.0 5 : 1.0 - 10 6 : >10.0
O	Spall (color)	Same as K "Metal strip (color)".
P	Spall (particle size)	P : Powder S : Small <1/32 in. diameter M : Medium 1/32 - 1/8 L : Large >1/8
Q	Spall (magnetic properties)	ND : Not Detectable W : Weak S : Strong

PRECEDING PAGE BLANK NOT FILMED.

TABLE A1-1 . NUMERICAL DATA TABULATION: ALLOY 1, N 155.

EXPOSURE TIME HOURS	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10⁻³ in	AVERAGE OXIDE THICKNESS 10⁻³ in	MAX DEPTH OF PENETRATION 10⁻³ in	MECHANICAL PROPERTIES: YIELD STRENGTH 10³ psi	ULTIMATE STRENGTH 10³ psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.3	0.0	0.0	0.1	<0.05	0	42.1	100.7	56	IC	S	ND	1	B	P	ND
16	0.5	0.0	0.0	0.2	<0.05	0	43.2	96.5	35	IC	S	ND	1	B	P	ND
64	0.6	0.4	0.0	0.3	0.05	0	42.5	100.0	35	IC	S	ND	1	B	P	ND
100	0.8	0.8	0.0	0.3	0.05	0	47.0	93.1	21	IC	S	ND	1	B	P	ND
200	0.9	0.6	0.0	0.4	0.05	0	47.8	89.7	19	LBr	S	ND	1	B	P	ND
300	1.3	1.3	0.0	0.4	0.05	0	55.6	102.1	11	LBr	P	ND	1	B	P	ND
400	1.1	0.8	0.0	0.3	0.05	0	49.4	91.2	10	LG	P	ND	1	B	P	ND
500	1.3	1.5	0.1	0.3	0.05	0	55.5	110.5	11	G	P	ND	1	B	P	ND
600	1.4	1.6	0.1	0.3	0.08	0	52.0	99.0	6	G	P	ND	1	B	P	ND
600c	1.3	-	0.0	0.3	-	0	56.3	102.2	7	G	P	ND	1	B	P	ND
Temperature 1600°F																
4	0.5	0.7	0.0	0.2	<0.05	0	45.9	100.0	36	LBr	S	ND	1	B	P	ND
16	1.0	1.2	0.0	0.2	0.10	0	48.4	100.5	25	G	P	ND	1	B	P	ND
64	1.0	1.2	0.1	0.3	0.10	0	48.0	100.3	20	G	P	W	1	B	P	ND
100	1.6	2.6	0.5	0.4	0.15	0	47.8	98.6	14	G	P	W	2	B	P	ND
200	1.5	2.2	0.4	0.3	0.15	0	47.5	98.0	11	G	P	W	2	B	P	ND
300	1.3	3.0	1.2	0.4	0.15	0	44.0	94.3	11	G	P	W	2	B	P	ND
400	1.8	2.7	1.3	0.6	0.20	0	49.4	102.5	12	G	P	W	2	B	P	ND
500	2.3	4.4	4.8	0.5	0.20	0	49.1	103.8	11	G	P	W	3	B	P	ND
600	1.4	2.6	1.9	0.3	0.25	0	48.1	97.1	11	G	P	W	3	B	P	ND
600c	2.2	3.9	4.8	0.3	0.20	0	44.0	92.6	11	G	P	W	3	B	P	ND
Temperature 1800°F																
4	0.1	1.0	0.6	0.5	<0.1	0	40.4	96.5	28	G	P	ND	2	B	P	S
16	2.5	3.9	4.1	0.5	0.1	0.3	44.1	102.0	31	G	P	ND	3	B	P	S
64	0.6	2.4	3.7	0.6	0.2	0.5	39.4	89.6	23	G	P	ND	3	B	P	S
100	3.6	7.3	7.8	0.5	0.2	0.5	38.9	91.9	22	G	PF	W	3	B	P	S
200	3.0	5.0	11.8	0.6	0.2	0.7	38.9	86.0	20	G	PF	W	3	B	P	S
300	13.6	15.6	24.6	0.6	0.2	2.2	34.2	91.9	27	G	PF	W	4	B	P	S
400	8.7	11.4	13.8	0.7	-	1.7	37.7	95.0	28	G	PF	W	3	B	P	S
500	27.0	19.1	17.1	2.0	-	1.5	33.6	87.5	26	G	PF	W	4	B	P	S
600	19.9	12.7	16.6	1.9	0.8	2.5	36.2	90.5	25	G	F	W	4	B	P	S
600c	11.6	21.9	36.3	1.2	-	-	36.9	86.9	26	G	F	W	4	B	P	S

TABLE A1-1 NUMERICAL DATA TABULATION: ALLOY 1, N 155.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	2.9	2.6	13.8	0.6	0.2	0	41.3	98.1	47	G	PF	ND	3	B	S	S
16	17.1	19.0	28.1	1.4	0.5	1.0	40.2	94.8	39	G	P	W	4	B	S	S
64	21.4	21.7	40.4	1.3	0.5	1.5	39.9	94.0	34	G	L	W	4	B	S	S
100	57.4	60.5	146.9	2.5	-	3.0	34.4	83.4	35	G	L	W	4	B	S	S
200	49.6	52.3	136.0	3.1	-	3.5	36.9	85.0	30	G	L	W	4	B	S	S
300	192.5	199.4	727.6	-4.4	1.0	4.0	36.0	79.1	36	G	L	S	5	B	L	S
400	188.1	192.0	701.9	-3.9	1.0	4.0	35.9	79.6	34	G	L	S	5	B	L	S
500	370.3	378.8	1443.2	-12.4	1.0	4.5	41.1	75.8	29	GGr	L	S	6	B	L	S
600	426.7	325.6	1677.4	-16.4	1.0	4.0	39.2	76.8	30	GGr	L	S	6	B	L	S
600c	324.2	433.4	1252.5	-11.7	-	-	47.8	62.5	8	GGr	L	S	6	B	L	S
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																

TABLE A1-2 NUMERICAL DATA TABULATION: ALLOY 2, TD NICKEL.

	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in²	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	1.9	1.9	0.0	0.2	0.1	0	41.3	65.7	18	GGr	S	S	ND	-	-	-
16	2.4	2.4	0.0	0.2	0.2	0	41.0	64.2	16	GGr	S	S	ND	-	-	-
64	3.2	3.0	0.1	0.2	-	0	41.9	63.4	15	GGr	S	S	ND	-	-	-
100	3.7	3.9	0.0	0.1	0.4	0	41.5	63.4	15	GGr	S	S	ND	-	-	-
200	4.3	3.8	0.0	0.2	0.4	0	41.7	62.5	18	GGr	S	S	ND	-	-	-
300	5.6	5.5	0.0	0.3	0.5	0	40.6	62.2	16	GGr	S	S	ND	-	-	-
400	5.2	4.7	0.0	0.4	0.3	0	40.8	62.0	15	GGr	S	S	ND	-	-	-
500	5.9	5.7	0.1	0.5	0.5	0	42.0	62.6	16	GGr	S	S	1	-	P	ND
600	6.1	5.4	0.1	0.1	0.4	0	41.2	62.3	15	GGr	S	S	1	-	P	ND
600c	5.5	5.8	0.1	0.5	-	-	40.6	61.6	15	GGr	S	S	1	-	P	ND
Temperature 1600°F																
4	2.8	2.8	0.0	0.2	0.1	0	41.6	64.7	17	GGr	S	S	ND	-	-	-
16	9.7	5.1	0.0	0.2	0.15	0	41.7	62.5	18	GGr	S	S	ND	-	-	-
64	7.2	7.0	0.0	0.3	0.7	0	42.7	62.5	15	GGr	S	S	1	Gr	P	ND
100	9.5	9.5	0.0	0.5	0.9	0	41.8	62.3	16	GGr	S	S	1	Gr	P	ND
200	11.6	11.3	0.8	0.7	-	0	41.3	62.2	16	Gr	S	S	2	Gr	P	ND
300	15.2	15.4	0.0	0.6	0.9	0	41.5	61.2	15	Gr	S	S	1	Gr	P	ND
400	16.2	16.0	0.0	0.7	0.9	0	41.0	61.5	16	Gr	S	S	1	Gr	P	ND
500	21.7	21.7	0.2	1.3	0.9	0	40.7	62.4	17	Gr	S	S	2	Gr	P	ND
600	21.1	20.8	0.1	1.1	1.0	0	41.9	62.0	15	Gr	S	S	1	Gr	P	ND
600c	23.6	23.4	0.4	1.2	-	-	41.1	61.0	16	Gr	S	S	2	Gr	P	ND
Temperature 1800°F																
4	5.7	5.5	0.1	0.3	0.3	0	41.1	61.5	15	Gr	S	S	1	Gr	S	ND
16	12.9	12.9	0.9	0.8	0.7	0	41.4	61.1	16	Gr	S	S	2	Gr	M	ND
64	19.8	19.6	0.2	1.2	1.0	0	40.5	61.6	15	Gr	S	S	2	Gr	M	ND
100	32.9	32.7	10.1	1.6	1.7	0	39.8	59.9	16	Gr	F	S	3	Gr	M	ND
200	72.2	72.2	78.0	5.0	-	0	42.3	64.5	16	Gr	L	S	4	G	M	ND
300	70.7	70.9	237.7	1.6	3.5	0	42.8	64.1	16	Gr	L	S	5	GGr	L	ND
400	79.8	83.4	137.7	1.6	3.5	0	39.1	57.9	15	Gr	L	S	4	GGr	L	ND
500	17.1	96.9	110.4	1.0	4.5	0	38.9	57.7	16	Gr	L	S	4	GGr	L	ND
600	108.7	99.7	153.5	1.4	4.0	0	39.0	59.2	18	Gr	L	S	5	GGr	L	ND
600c	100.4	108.6	158.1	1.3	-	-	38.4	58.0	16	Gr	L	S	5	GGr	L	ND

TABLE A1-2 NUMERICAL DATA TABULATION: ALLOY 2, TD NICKEL.

	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 INDIR.	SPECIFIC SPALL WEIGHT mg/in^2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000 °F																
4	2.9	14.8	13.8	0.9	0.5	0	40.5	61.0	16	Gr	S	S	1	Gr	S	ND
16	33.9	34.0	32.1	1.8	1.6	0	39.3	59.4	15	Gr	L	S	4	Gr	S	W
64	63.8	62.7	117.0	2.0	2.7	0	38.7	59.9	18	Gr	L	S	4	GGr	L	W
100	91.5	92.8	65.4	2.6	4.5	0	38.0	57.4	16	Gr	L	S	4	GGr	L	W
200	121.2	119.0	180.1	2.1	5.5	0	38.0	56.7	15	Gr	L	S	5	GGr	L	W
300	159.1	158.1	104.0	6.2	7.5	0	34.8	50.0	15	G	L	S	4	GGr	L	W
400	178.7	85.2	111.7	5.7	9.5	0	32.3	47.8	16	G	L	S	4	GGr	L	W
500	225.0	221.0	46.3	7.3	10.0	0	33.8	50.7	16	G	L	S	4	GGr	L	W
600	261.7	201.8	97.6	8.5	11.0	0	30.7	51.9	15	G	L	S	4	GGr	L	W
600c	212.8	255.4	38.5	8.7	-	-	40.0	60.0	13	G	L	S	4	GGr	L	W
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																

TABLE A1-3 NUMERICAL DATA TABULATION: ALLOY 3, TD NICKEL-CHROMIUM.

	Weight Gain & Thickness Change						Mechanical Properties			Metal Strip			Spall			
Exposure Time Hours	Specific Total Weight Gain mg/in² DIR.	Specific Total Weight Gain mg/in² INDIR.	Specific Spall Weight mg/in2	Thickness Change 10^{-3} in	Average Oxide Thickness 10^{-3} in	Max Depth of Penetration 10^{-3} in	Yield Strength 10^3 psi	Ultimate Strength 10^3 psi	Elongation Percentage 1.0 in	Color	Texture	Magnetic Properties	Amount	Color	Particle Size	Magnetic Properties
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.3	0.3	0.0	0.0	<0.05	0	91.1	132.8	20	LGr	S	ND	ND	-	-	-
16	0.4	0.3	0.0	0.0	<0.05	0	90.6	131.2	19	LGr	S	ND	ND	-	-	-
64	0.6	-	0.0	0.2	<0.05	0	90.9	132.4	20	LGr	S	ND	ND	-	-	-
100	0.5	-	0.0	0.2	<0.05	0	92.4	133.8	20	LGr	S	ND	ND	-	-	-
200	0.8	0.3	0.1	0.6	<0.05	0	88.5	130.9	18	LGr	S	ND	ND	-	-	-
300	0.8	0.6	0.0	0.2	<0.05	0	95.6	136.2	18	LGr	S	ND	ND	-	-	-
400	0.9	0.5	0.0	0.2	<0.05	0	94.7	136.5	19	LGr	S	ND	ND	-	-	-
500	0.9	0.8	0.0	0.2	<0.05	0	84.8	131.2	17	LGr	S	ND	ND	-	-	-
600	0.9	1.0	0.0	0.5	<0.05	0	90.8	133.5	19	LGr	S	ND	ND	-	-	-
600c	1.0	0.5	0.1	0.2	-	-	91.0	131.7	21	LGr	S	ND	ND	-	-	-
Temperature 1600°F																
4	0.3	-	0.0	0.2	<0.05	0	91.6	132.2	19	LGr	S	ND	ND	-	-	-
16	0.4	0.6	0.0	0.0	<0.05	0	90.4	132.0	19	LGr	S	ND	ND	-	-	-
64	0.6	0.6	0.0	0.0	<0.05	0	92.8	133.7	20	LGr	S	ND	ND	-	-	-
100	0.8	1.9	0.0	0.2	<0.05	0	96.1	136.3	20	LGr	S	ND	ND	-	-	-
200	0.8	0.7	0.0	0.2	<0.05	0	94.0	136.3	20	LGr	S	ND	ND	-	-	-
300	1.1	1.3	0.0	0.2	<0.05	0	93.7	136.0	21	LGr	S	ND	ND	-	-	-
400	1.3	1.4	0.0	0.2	<0.05	0	93.5	135.4	19	LGr	S	ND	ND	-	-	-
500	1.3	1.5	0.2	0.4	<0.05	0	95.9	136.8	19	LGr	S	ND	1	B	P	W
600	1.4	1.1	0.2	0.4	<0.1	0	92.2	135.1	20	LGr	S	ND	1	B	P	W
600c	1.5	1.8	0.1	0.4	<0.1	-	92.2	135.0	20	LGr	S	ND	1	B	P	W
Temperature 1800°F																
4	0.7	0.5	0.0	0.3	<0.05	0	92.2	136.2	22	LGr	S	ND	ND	-	-	-
16	1.0	1.1	0.0	0.3	<0.05	0	93.4	135.8	21	LGr	S	ND	ND	-	-	-
64	1.5	1.5	0.2	0.7	<0.05	0	94.7	137.4	19	LGr	S	ND	1	B	P	W
100	1.6	1.8	0.1	0.4	<0.05	0	92.8	135.1	20	GGr	S	ND	1	B	P	W
200	1.8	2.3	0.1	0.3	<0.05	0	91.1	134.8	19	GGr	S	ND	1	B	P	W
300	2.0	6.2	0.2	0.3	<0.05	0	88.0	134.1	21	GGr	S	ND	1	B	P	W
400	2.0	3.0	0.3	0.4	0.05	0	92.3	134.7	20	GGr	S	ND	2	B	P	W
500	2.1	2.1	0.4	0.3	0.1	0	92.2	133.0	18	GGr	S	ND	2	B	P	W
600	2.5	3.1	0.5	0.4	0.1	0	92.2	133.4	20	GGr	S	ND	2	B	P	W
600c	2.4	3.5	0.6	0.7	-	-	90.3	132.0	21	GGr	S	ND	2	B	P	W

TABLE A1-3 NUMERICAL DATA TABULATION: ALLOY 3, TD NICKEL-CHROMIUM.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	1.2	1.3	0.1	0.2	0.05	0	90.4	132.6	21	Gr	S	ND	1	B	P	W
16	1.7	2.0	0.2	0.2	0.1	0	90.4	132.8	20	GGr	S	ND	1	B	P	W
64	3.0	-	0.9	0.3	0.1	0	89.6	131.9	21	GGr	S	ND	2	B	P	W
100	3.1	3.5	0.5	0.7	0.1	0	90.4	133.0	20	GGr	S	ND	2	B	P	W
200	3.0	3.3	0.7	0.4	0.1	0	89.5	132.0	22	GGr	S	ND	2	B	P	W
300	3.0	4.9	1.0	0.3	0.15	0	88.7	131.3	20	GGr	S	ND	2	B	P	W
400	3.5	4.0	2.0	0.4	0.15	0	89.6	131.8	20	GGr	S	ND	3	B	P	W
500	4.2	6.3	3.1	0.5	0.15	0	89.4	132.3	21	GGr	S	ND	3	B	P	W
600	5.2	1.9	4.5	0.5	0.2	0	88.0	131.0	19	GGr	S	ND	3	B	P	W
600c	3.4	4.6	2.1	0.5	-	-	89.2	131.0	20	GGr	S	ND	3	B	P	W
Temperature 2100°F																
4	2.1	2.3	0.1	0.2	0.1	0	85.0	132.0	18	GGr	S	ND	1	B	P	W
16	3.5	3.0	0.2	0.4	0.2	0	87.5	133.0	19	GGr	SP	ND	2	B	P	W
64	4.0	3.6	0.6	0.5	0.2	0	87.0	130.2	18	GGr	SP	ND	2	B	P	W
100	4.1	4.4	0.7	0.5	-	0	86.9	131.0	15	GGr	SP	ND	2	B	P	W
200	2.0	3.6	0.6	0.5	0.3	0	78.7	133.1	19	GGr	SP	ND	2	B	P	W
300	2.7	4.5	1.0	0.7	0.3	0	86.1	132.7	18	GGr	SP	ND	2	B	P	W
400	0.6	1.1	0.6	0.5	0.3	0	86.4	133.5	19	GGr	SP	ND	2	B	P	W
500	1.5	2.8	1.5	0.5	0.3	0	87.5	132.9	19	GGr	SP	ND	3	B	P	W
600	-1.5	5.9	8.0	0.3	0.3	0	85.4	131.3	19	GGr	SP	ND	2	B	P	W
600c	1.6	6.8	1.8	0.6	-	-	89.4	136.0	18	GGr	SP	ND	3	B	P	W
Temperature 2200°F																
4	3.1	3.4	0.4	0.6	0.1	0	88.1	136.8	18	GGr	SP	ND	1	B	P	W
16	3.5	4.0	0.4	0.6	0.1	0	77.5	134.0	18	GGr	SP	ND	1	B	P	W
64	3.2	5.0	1.3	0.6	0.2	0	80.6	135.0	16	GGr	SP	ND	1	B	P	W
100	2.4	7.4	1.5	0.9	-	0	88.7	133.8	19	GGr	SP	ND	2	B	P	W
200	-0.2	11.9	2.2	0.9	-	0	73.5	132.5	13	GGr	SP	ND	2	B	P	W
300	-1.7	16.9	1.9	0.8	-	0	81.9	132.1	18	GGr	SP	ND	2	B	P	W
400	-6.0	6.9	1.3	0.9	0.7	0	79.3	132.6	18	GGr	SP	ND	1	B	P	W
500	-7.0	8.4	1.4	0.9	0.7	0	85.4	131.5	18	GGr	SP	ND	1	B	P	W
600	-1.0	-	1.9	0.7	0.7	0	86.4	131.0	19	GGr	SP	ND	2	B	M	W
600c	-8.0	-	3.4	0.7	-	-	84.4	131.0	20	GGr	SP	ND	2	B	M	W

TABLE A1-4 NUMERICAL DATA TABULATION: ALLOY 4, BENDEL 65-35.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 INDIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1600°F (No 1400°F series)																
4	0.6	0.7	0.0	0.0	<0.05	0	45.5	92.5	32	G	S	ND	1	B	P	ND
16	0.8	0.9	0.0	0.0	0.05	0	43.2	88.5	34	G	S	ND	1	B	P	ND
64	0.8	1.5	0.0	0.0	0.1	0	42.0	83.1	29	G	P	ND	1	B	P	ND
100	1.1	2.1	0.8	0.6	0.1	0	40.4	81.6	31	G	P	ND	2	B	P	ND
200	1.2	2.2	1.0	0.4	-	0	47.9	94.5	34	G	P	ND	2	B	P	ND
300	1.3	2.9	1.5	0.3	-	0	47.1	91.2	28	G	P	ND	3	B	P	ND
400	1.8	3.5	3.5	0.2	0.4	0	45.6	92.7	32	G	P	ND	3	B	P	ND
500	2.8	4.8	6.7	0.2	0.4	0	37.5	72.9	27	G	P	ND	3	B	P	ND
600	1.2	4.1	5.4	0.3	0.4	0	39.2	85.0	35	G	P	ND	3	B	P	ND
600c	1.8	4.4	6.1	0.3	-	-	51.0	98.0	30	G	P	ND	3	B	P	ND
Temperature 1800°F																
4	1.0	1.6	0.7	0.4	0.1	0	53.8	100.0	20	G	S	ND	2	B	P	ND
16	1.7	3.2	1.9	0.7	0.2	0	52.7	102.7	26	G	P	ND	2	B	P	ND
64	3.5	5.9	7.0	0.7	0.3	1.1	55.4	103.5	26	G	P	ND	3	B	P	ND
100	6.5	8.3	14.7	1.0	0.4	1.1	50.7	98.5	20	G	P	ND	3	B	P	ND
200	6.4	9.7	20.3	1.3	-	-	50.4	100.0	24	G	P	ND	3	B	P	ND
300	8.9	10.6	26.6	1.6	-	0.9	51.7	99.5	22	G	P	ND	4	B	P	ND
400	11.7	15.7	35.9	1.8	-	1.2	46.9	95.5	22	G	P	ND	4	B	P	ND
500	12.7	15.8	38.3	1.3	-	0.7	47.6	92.5	20	G	P	ND	4	B	P	ND
600	12.7	17.7	43.5	1.6	1.0	1.5	49.1	91.0	21	G	P	ND	4	B	P	ND
600c	14.5	15.4	37.3	1.5	-	-	50.7	94.0	17	G	P	ND	4	B	P	ND
Temperature 2000°F																
4	2.9	4.5	7.3	0.6	0.1	0.9	52.3	99.0	19	G	S	ND	3	B	P	W
16	4.3	5.9	14.6	0.5	0.2	1.2	46.6	97.2	22	GGr	P	ND	3	B	P	W
64	11.0	14.3	41.7	0.5	0.5	1.5	48.2	95.8	21	GGr	P	ND	4	B	P	W
100	16.2	19.2	54.1	1.7	-	-	47.4	88.3	18	GGr	P	ND	4	B	P	W
200	27.7	31.2	79.9	0.6	-	3.0	50.0	92.5	20	GGr	P	ND	4	B	P	W
300	31.7	35.7	99.2	0.7	-	-	48.7	80.4	16	GGr	P	ND	4	B	P	W
400	45.7	-	134.0	0.2	1.5	4.2	46.1	85.5	17	GGr	P	ND	4	B	P	W
500	45.1	62.5	148.8	0.5	1.5	-	46.0	87.9	15	GGr	P	ND	4	B	P	W
600	37.8	56.9	131.3	0.5	1.5	-	39.4	79.0	17	GGr	P	ND	4	B	P	W
600c	56.5	37.2	167.0	0.5	-	-	-	-	-	GGr	P	ND	4	B	P	W

TABLE A1-5 NUMERICAL DATA TABULATION: ALLOY 5, CHROMEL A.

EXPOSURE TIME HOURS	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in²	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.3	0.4	0.0	0.1	<0.05	0	25.6	89.4	44	IC	S	ND	ND	–	–	–
16	0.3	0.4	0.0	0.1	<0.05	0	25.5	89.5	44	IC	S	ND	ND	–	–	–
64	0.5	–	0.0	0.2	<0.05	0	25.6	91.5	48	IC	S	ND	ND	–	–	–
100	0.4	0.4	0.0	0.1	<0.05	0	29.4	91.2	45	IC	S	ND	1	B	P	ND
200	0.7	0.4	0.0	0.2	<0.05	0	24.4	90.4	45	GGr	S	ND	1	B	P	ND
300	1.6	0.6	0.0	0.1	<0.05	0	30.0	92.8	42	GGr	S	ND	1	B	P	ND
400	0.8	0.6	0.1	0.2	<0.05	0	23.3	91.0	41	GGr	S	ND	1	B	P	ND
500	0.7	0.5	0.0	0.3	<0.05	0	27.6	90.3	45	GGr	S	ND	1	B	P	ND
600	0.8	0.9	0.1	0.2	<0.05	0	27.6	88.5	42	GGr	S	ND	1	B	P	ND
600c	0.9	0.5	0.1	0.2	–	0	29.9	102.0	45	GGr	S	ND	1	B	P	ND
Temperature 1600°F																
4	0.4	0.5	0.0	0.0	–	0	26.6	–	43	Gr	S	ND	1	B	P	ND
16	0.6	0.6	0.0	0.1	–	0	29.6	92.4	43	Gr	S	ND	1	B	P	ND
64	0.9	1.0	0.0	0.1	0.1	0	27.6	91.0	44	GGr	S	ND	1	B	P	ND
100	0.9	0.9	0.0	0.2	0.1	0	25.9	93.3	43	GGr	S	ND	1	B	P	ND
200	1.0	1.0	0.0	0.2	0.1	0	25.0	93.9	45	G	S	ND	1	B	P	ND
300	1.2	–	0.0	0.2	–	0	22.2	75.5	45	G	P	ND	1	B	P	ND
400	1.2	–	0.2	0.2	–	0	21.5	73.0	40	G	P	ND	2	B	P	ND
500	0.8	1.5	0.2	1.0	–	0	23.5	74.0	45	G	P	ND	2	B	P	ND
600	1.2	1.8	0.6	0.2	0.1	0	26.5	94.5	43	G	P	ND	2	B	P	ND
600c	1.0	1.8	0.3	0.3	–	–	24.9	94.0	43	G	P	ND	2	B	P	ND
Temperature 1800°F																
4	1.3	1.2	0.1	0.4	<0.05	0	28.8	92.7	44	LG	SF	ND	2	GB	P	W
16	1.0	1.6	0.2	0.3	0.1	0	29.4	91.5	43	LG	F	ND	3	GB	P	W
64	0.2	2.3	1.9	0.3	0.1	0	29.1	91.9	45	LG	P	ND	3	GB	P	W
100	0.6	3.3	3.7	0.5	0.2	1.2	25.4	90.6	45	LG	P	ND	4	GB	P	W
200	2.1	4.5	9.7	0.6	0.3	3.3	25.0	91.0	42	LG	P	ND	4	GB	P	W
300	2.1	4.6	10.8	0.8	0.5	3.5	26.2	91.5	43	LG	P	ND	4	GB	P	W
400	5.0	8.0	17.3	1.0	0.5	4.0	25.0	90.4	43	G	P	ND	4	GB	P	W
500	4.0	7.0	16.6	0.8	0.7	4.0	25.2	94.8	40	G	P	ND	4	GB	P	W
600	5.4	10.5	20.5	0.7	0.7	4.0	29.9	94.5	41	G	P	ND	4	GB	P	W
600c	7.6	9.0	24.9	0.9	–	–	30.5	95.4	42	G	P	ND	4	GB	P	W

TABLE A1-5 NUMERICAL DATA TABULATION: ALLOY 5, CHROMEL A.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in^2		SPECIFIC SPALL WEIGHT mg/in^2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
	DIR.	INDIR.														
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	1.5	2.6	1.1	0.4	<0.1	-	27.4	92.0	45	LG	P	ND	2	GB	P	W
16	1.8	4.0	5.5	0.9	0.2	-	28.5	92.7	47	LG	P	ND	3	GB	P	W
64	10.4	14.4	13.1	2.0	0.7	-	28.3	88.5	43	GB	P	ND	3	GB	P	W
100	13.1	2.8	16.4	2.2	-	-	26.1	86.3	44	GB	P	ND	4	GB	P	W
200	12.8	24.3	27.0	2.7	-	1.0	25.2	84.4	42	GB	P	ND	4	GB	P	W
300	23.4	30.4	50.7	3.3	-	3.5	27.4	83.9	44	GB	P	ND	4	GB	P	W
400	24.2	35.0	77.6	0.8	-	6.0	28.0	86.4	42	LG	P	ND	4	GB	P	W
500	27.6	37.6	97.2	0.6	1.3	5.0	27.8	85.4	40	LG	P	ND	4	GB	P	W
600	27.9	42.0	108.2	-0.3	1.3	6.0	26.1	86.0	39	LG	P	ND	4	GB	P	W
600c	30.1	38.7	115.5	-0.4	-	-	27.0	85.5	41	LG	P	ND	4	GB	P	W
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																

TABLE A1-6 NUMERICAL DATA TABULATION: ALLOY 6, DH 242.

	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP				SPALL			
EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.3	0.3	0.0	0.1	<0.05	0	34.0	94.2	44	IC	S	ND	ND	-	-	-
16	0.2	0.3	0.0	0.1	-	0	31.0	93.5	52	IC	S	ND	ND	-	-	-
64	0.5	0.4	0.0	0.1	-	0	33.1	90.5	48	Br	S	ND	ND	-	-	-
100	0.4	0.4	0.0	0.0	-	0	32.0	89.2	45	Br	S	ND	ND	-	-	-
200	0.7	0.3	0.0	0.1	0.05	0	31.8	89.4	50	BGr	S	ND	ND	-	-	-
300	0.6	0.6	0.0	0.2	0.05	0	31.5	90.8	49	BGr	S	ND	ND	-	-	-
400	0.8	0.7	0.0	0.3	0.05	0	30.8	89.2	48	BGr	S	ND	ND	-	-	-
500	0.6	0.7	0.0	0.1	0.05	0	34.5	97.0	52	BGr	S	ND	ND	-	-	-
600	0.7	1.1	0.1	0.1	0.1	0	32.5	92.5	47	BGr	S	ND	ND	-	-	-
600c	0.9	1.1	0.1	0.2	-	-	34.9	94.5	45	BGr	S	ND	ND	-	-	-
Temperature 1600°F																
4	0.5	0.6	0.0	0.0	0.05	0	32.8	93.5	46	Gr	S	ND	ND	-	-	-
16	0.7	1.1	0.0	0.3	0.05	0	33.6	93.7	50	Gr	S	ND	ND	-	-	-
64	1.2	1.3	0.0	0.1	0.1	0	32.9	93.4	46	GGr	P	ND	ND	-	-	-
100	0.9	1.0	0.0	0.2	0.1	0	32.2	93.5	52	GGr	P	ND	ND	-	-	-
200	1.1	1.2	0.1	0.3	0.15	0	32.7	95.5	49	G	P	ND	ND	-	-	-
300	1.3	2.0	0.1	0.2	-	0	32.0	93.5	46	G	P	ND	ND	-	-	-
400	1.4	2.2	0.1	0.3	-	0	32.2	93.8	45	G	P	ND	1	B	P	ND
500	1.2	1.7	0.3	0.2	0.4	0	33.1	94.4	48	G	P	ND	1	B	P	ND
600	1.5	2.4	0.7	0.2	0.4	0	32.3	93.6	45	G	P	ND	1	B	P	ND
600c	1.3	2.7	0.3	0.2	-	-	32.7	94.4	50	G	P	ND	1	B	P	ND
Temperature 1800°F																
4	1.6	1.5	0.1	0.0	<0.1	-	33.0	93.0	47	GGr	P	ND	1	B	P	ND
16	1.6	1.7	0.1	0.1	-	-	34.9	92.1	49	GGr	P	ND	1	B	P	ND
64	1.4	3.2	1.8	0.3	0.1	0.6	32.6	94.0	50	B	P	ND	3	B	P	W
100	1.8	3.6	1.4	0.5	0.2	0.8	32.8	94.0	50	B	P	ND	2	B	P	W
200	4.2	6.5	7.1	0.7	0.2	1.3	32.0	92.0	43	B	P	ND	3	B	P	W
300	4.2	6.6	3.9	0.4	0.2	0.5	33.2	90.6	47	B	P	ND	3	B	P	W
400	6.4	9.5	6.9	0.8	0.5	1.9	31.5	90.8	47	GB	P	ND	3	B	P	W
500	4.0	-	16.6	0.7	0.6	1.9	31.3	92.4	49	GB	P	ND	3	B	P	W
600	6.1	11.0	9.3	0.5	0.6	2.9	30.3	89.3	47	GB	P	ND	3	B	P	W
600c	8.9	8.4	12.3	1.4	-	-	30.7	89.6	43	GB	P	ND	3	B	P	W

TABLE A1-6 NUMERICAL DATA TABULATION: ALLOY 6, DH 242.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP COLOR	METAL STRIP TEXTURE	METAL STRIP MAGNETIC PROPERTIES	SPALL AMOUNT	SPALL COLOR	SPALL PARTICLE SIZE	SPALL MAGNETIC PROPERTIES
	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	4.0	4.2	0.3	0.6	0.15	0.55	31.5	93.3	51	Gr	P	ND	2	B	P	W
16	4.6	5.5	2.4	0.6	0.2	0.7	32.0	92.8	50	Gr	P	ND	3	B	P	W
64	2.6	13.5	0.3	1.6	0.2	1.2	31.5	90.0	45	GB	P	ND	3	B	P	W
100	12.6	13.8	9.6	1.7	0.2	2.2	32.9	89.0	50	GB	P	ND	3	B	P	W
200	17.9	20.0	23.1	2.0	-	2.7	32.2	88.7	46	BGr	P	ND	4	B	P	W
300	19.2	26.3	33.1	2.2	-	4.0	30.2	84.0	44	BGr	Pt	ND	4	B	P	W
400	22.2	28.0	47.7	2.8	-	3.5	29.4	82.0	44	GGr	Pt	ND	4	B	P	W
500	18.9	22.7	43.1	1.8	1.1	6.5	29.4	84.0	48	GGr	Pt	ND	4	B	P	W
600	18.7	37.9	62.9	0.7	1.1	6.5	28.8	80.3	44	GGr	Pt	ND	4	B	P	W
600c	23.4	31.7	64.6	1.8	-	-	28.1	82.1	45	GGr	Pt	ND	4	B	P	W
Temperature 2100°F																
4	5.7	7.0	2.7	0.8	0.1	0.6	25.6	93.5	35	GGr	F	ND	3	GB	P	ND
16	8.5	10.6	3.8	1.0	0.2	0.3	30.1	90.6	33	GB	F	ND	3	GB	P	W
64	14.1	18.9	8.8	1.3	0.5	0.5	26.3	89.8	47	BGr	F	ND	3	GB	P	W
100	17.5	21.9	26.5	2.1	-	1.5	27.7	87.9	44	GGr	L	ND	4	GB	P	W
200	16.6	25.7	43.4	1.5	-	-	28.2	90.1	43	GGr	L	ND	4	GB	P	W
300	16.8	26.7	58.5	1.2	-	-	25.9	89.8	47	Gr	L	ND	4	GB	P	W
400	29.5	36.5	101.8	0.9	1.3	-	29.8	87.7	43	Gr	L	ND	4	GB	P	W
500	28.9	39.5	117.5	0.2	2.3	-	28.4	86.0	39	Gr	L	ND	4	GB	P	W
600	30.5	48.4	131.2	1.0	2.3	6.0	27.0	87.3	42	Gr	L	ND	4	GB	P	W
600c	29.3	56.2	137.0	-0.2	-	-	28.1	87.5	40	Gr	L	ND	4	GB	P	W
Temperature 2200°F																
4	11.1	12.0	4.1	0.7	0.2	0.7	28.5	92.4	43	GGr	F	ND	3	GB	P	W
16	12.9	15.8	12.3	1.5	0.3	-	26.3	92.2	43	GGr	L	ND	3	GB	P	W
64	29.2	36.5	22.4	1.5	-	-	28.8	92.0	45	GGr	L	ND	4	GB	P	W
100	62.1	41.2	33.0	1.0	-	-	28.2	82.5	37	Gr	L	ND	4	GB	P	W
200	24.9	45.9	100.3	-0.4	-	-	27.6	85.3	44	Gr	L	ND	4	GB	P	W
300	34.4	57.0	155.5	0.1	-	-	26.9	79.9	38	Gr	L	ND	5	GB	P	W
400	-	61.4	56.7	-0.9	-	-	29.2	80.0	36	Gr	L	ND	4	GB	P	W
500	76.5	99.9	302.9	-0.8	-	-	25.2	76.1	33	Gr	L	ND	5	GB	P	W
600	117.8	142.8	445.8	-1.5	2.5	7.5	25.7	68.8	28	Gr	L	ND	5	GB	P	W
600c	130.1	143.0	521.6	-1.5	-	-	23.2	67.5	30	Gr	L	ND	5	GB	P	W

TABLE A1-7 NUMERICAL DATA TABULATION: ALLOY 7, GE 1541.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC SPALL WEIGHT mg/in²	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.8	0.9	0.0	0.0	0.05	0	40.3	69.1	24	IC	S	S	ND	-	-	-
16	1.1	1.0	0.0	0.1	0.05	0	43.5	69.1	23	IC	S	S	ND	-	-	-
64	0.8	0.5	0.0	0.2	0.05	0	46.5	67.1	19	IC	S	S	ND	-	-	-
100	0.9	0.9	0.0	0.0	0.05	0	44.2	69.0	28	IC	S	S	ND	-	-	-
200	1.0	0.4	0.0	0.6	0.05	0	47.0	68.9	23	IC	S	S	ND	-	-	-
300	0.8	0.7	0.0	0.2	0.1	0	47.7	69.5	25	IC	S	S	ND	-	-	-
400	0.9	0.5	0.0	0.5	0.1	0	47.7	70.6	25	IC	S	S	ND	-	-	-
500	0.9	0.9	0.1	0.5	0.1	0	45.7	67.8	19	IC	S	S	1	B	S	W
600	1.1	1.6	0.1	0.3	0.1	0	47.1	70.1	28	IC	S	S	1	B	S	W
600c	1.2	1.1	0.1	0.4	-	-	44.1	66.6	25	IC	S	S	1	B	S	W
Temperature 1600°F																
4	0.5	0.6	0.0	0.3	0.05	0	47.7	70.8	27	IC	S	S	1	B	S	W
16	0.8	0.7	0.0	0.2	0.05	0	42.2	71.5	25	IC	S	S	1	B	S	W
64	1.1	0.9	0.0	0.4	0.1	0	48.4	71.1	23	IC	S	S	1	B	S	W
100	1.2	1.5	0.1	0.3	0.1	0	45.1	72.0	28	IC	S	S	1	B	S	W
200	1.2	0.6	0.0	0.2	0.15	0.25	48.4	71.6	21	IC	S	S	1	B	S	W
300	1.4	1.6	0.1	0.2	0.1	1.1	45.8	69.6	25	IC	S	S	1	B	S	W
400	1.6	1.2	0.1	0.2	0.1	1.1	47.4	71.8	26	IC	S	S	1	B	S	W
500	1.9	2.2	0.2	0.3	0.1	1.6	46.1	72.3	23	LG	S	S	2	B	S	W
600	1.7	1.8	0.2	0.2	0.1	-	48.0	70.6	24	LG	S	S	2	B	S	W
600c	2.0	1.8	0.3	0.2	-	-	46.5	70.4	23	LG	S	S	2	B	S	W
Temperature 1800°F																
4	0.8	0.5	0.0	0.2	0.1	0	49.0	72.0	23	IC	S	S	1	B	S	W
16	1.1	1.3	0.1	0.3	0.1	0	48.7	71.4	22	LG	S	S	1	B	S	W
64	1.4	1.0	0.1	0.4	0.1	0	47.4	72.1	23	LG	S	S	1	B	S	W
100	1.4	1.3	0.0	0.6	0.1	0	48.1	71.0	23	LG	S	S	1	B	S	W
200	2.0	2.0	0.2	0.3	0.1	0	47.1	71.0	25	LG	S	S	2	B	S	W
300	2.3	2.4	0.3	0.2	0.1	0	47.0	69.9	24	LG	S	S	2	B	S	W
400	2.3	1.8	0.1	0.3	0.1	0	46.0	69.4	20	LG	S	S	1	B	S	W
500	2.7	2.4	0.5	0.7	0.1	0	46.8	67.8	23	LG	S	S	2	B	S	S
600	3.1	1.1	0.6	0.3	0.1	4.5	45.5	68.7	24	LG	S	S	2	B	S	S
600c	2.8	3.0	0.5	0.3	-	-	46.6	67.6	22	LG	S	S	2	B	S	S

TABLE A1-7 NUMERICAL DATA TABULATION: ALLOY 7, GE 1541.

	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	1.1	0.9	0.1	0.3	0.15	1.15	47.7	71.1	22	LG	S	S	1	B	S	W
16	2.1	2.0	0.2	0.3	0.2	2.2	48.0	71.3	28	LG	S	S	2	B	S	W
64	2.6	1.0	0.3	0.1	0.2	2.7	42.8	70.0	27	LG	S	S	2	B	S	W
100	4.2	3.4	0.6	0.3	0.2	3.7	41.5	71.0	22	LG	S	S	2	B	S	W
200	3.8	0.6	0.5	0.3	0.2	3.2	41.8	69.6	23	LG	S	S	2	B	S	S
300	6.0	4.7	1.8	0.2	0.2	5.2	42.5	68.7	20	LG	S	S	2	B	S	S
400	4.6	8.7	0.5	0.2	0.3	4.3	38.4	68.7	22	LG	S	S	2	B	S	S
500	6.7	1.5	1.5	0.6	0.3	4.8	43.5	69.1	24	LG	S	S	2	B	S	S
600	8.6	-	2.5	0.3	0.2	-	46.3	69.5	22	LG	S	S	2	B	S	S
600c	7.2	1.3	1.4	0.4	-	-	36.4	75.4	21	LG	S	S	3	B	S	S
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																

TABLE A1-8 NUMERICAL DATA TABULATION: ALLOY 8, HOSKINS 875.

EXPOSURE TIME HOURS	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC TOTAL WEIGHT GAIN mg/in2 DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in2 INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.2	0.2	0.0	0.6	<0.5	0	25.6	25.6	0	IC	S	S	ND	-	-	-
16	0.2	1.2	0.0	0.1	<0.5	0	46.6	46.6	2	IC	S	S	ND	-	-	-
64	0.2	0.1	0.0	0.5	<0.5	0	37.8	37.8	1	IC	S	S	ND	-	-	-
100	0.3	0.3	0.0	0.1	<0.5	0	47.5	47.5	2	IC	S	S	ND	-	-	-
200	0.4	0.1	0.0	0.2	<0.5	0	51.3	51.3	1	IC	S	S	ND	-	-	-
300	0.7	0.5	0.0	0.2	<0.5	0	62.0	68.0	4	IC	S	S	ND	-	-	-
400	0.5	0.6	0.0	0.1	<0.5	0	61.6	66.2	3	LG	S	S	ND	-	-	-
500	0.8	0.7	0.0	0.1	<0.5	0	62.1	62.1	2	LG	S	S	ND	-	-	-
600	1.1	0.7	0.0	0.2	<0.5	0	45.4	45.4	1	LG	S	S	ND	B	S	W
600c	0.8	0.1	0.0	0.4	-	-	44.9	44.9	3	LG	S	S	1	B	S	W
Temperature 1600°F																
4	0.4	0.0	0.0	0.1	0	0	61.3	61.3	1	IC	S	S	ND	-	-	-
16	1.2	1.2	0.0	0.0	<0.05	0	62.9	73.5	4	LG	S	S	ND	-	-	-
64	1.8	1.6	0.0	0.2	0.05	0	67.3	75.5	5	LG	S	S	ND	-	-	-
100	2.3	2.3	0.0	0.3	0.1	0	67.2	69.1	2	LG	S	S	1	B	S	W
200	2.9	2.5	0.0	0.2	0.1	0	39.0	39.0	2	LG	S	S	1	B	S	W
300	3.4	3.3	0.0	0.3	0.1	0	46.5	46.5	2	LG	S	S	1	B	S	W
400	3.5	3.1	0.0	0.3	0.1	0	42.5	42.5	1	LG	S	S	1	B	S	W
500	4.3	4.2	0.2	0.2	0.1	0	67.0	67.0	1	LC	S	S	2	B	S	W
600	5.4	5.1	0.1	0.2	0.2	0	58.1	58.1	1	LG	S	S	2	B	S	W
600c	4.2	4.0	0.2	0.4	-	-	67.0	67.7	1	LG	S	S	2	B	S	W
Temperature 1800°F																
4	1.6	1.5	0.0	0.2	<0.05	0	50.0	50.0	1	LG	S	S	1	B	S	W
16	1.6	1.6	0.0	0.3	0.05	0	68.0	72.1	3	LG	S	S	1	B	S	W
64	2.6	2.4	0.0	0.2	0.1	0	49.7	49.7	1	LG	S	S	1	B	S	W
100	2.2	1.9	0.0	0.4	0.1	0	66.0	68.5	2	LG	S	S	1	B	S	W
200	2.3	2.2	0.2	0.7	0.15	0	58.3	58.3	2	LG	S	S	2	B	S	W
300	2.2	2.0	0.1	0.4	0.2	0	67.3	67.3	2	LG	S	S	2	B	S	W
400	2.8	2.4	0.2	0.4	0.2	0	67.0	67.0	1	LG	S	S	2	B	S	W
500	2.6	-	0.2	0.4	0.3	0	66.9	68.8	1	LG	S	S	2	B	S	W
600	2.8	2.4	0.8	0.4	0.3	0	67.3	67.3	1	LG	S	S	2	B	S	W
600c	2.7	-	0.4	0.2	-	-	43.6	43.6	1	LB	S	S	2	B	S	W

TABLE A1-8 NUMERICAL DATA TABULATION: ALLOY 8, HOSKINS 875.

	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	1.1	1.0	0.2	0.1	0.1	0	64.5	68.2	2	LG	S	S	2	B	S	W
16	1.6	1.4	0.2	0.1	0.1	0	11.2	11.2	0	LG	S	S	2	B	S	W
64	2.1	0.8	0.2	0.2	0.1	0	67.4	67.4	2	LG	S	S	2	B	S	S
100	2.9	4.8	0.2	0.1	0.15	0	66.3	66.3	1	LG	S	S	2	B	S	S
200	3.1	1.6	0.4	0.7	0.2	0	44.9	44.9	1	LG	S	S	2	B	S	S
300	5.3	4.8	1.3	0.4	0.1	0	10.6	10.6	0	LG	S	S	2	B	S	S
400	4.6	0.5	1.0	0.6	0.15	0	66.3	67.5	1	LG	S	S	2	B	S	S
500	6.6	4.4	1.9	0.6	0.15	0	51.0	51.0	1	LG	S	S	3	B	S	S
600	10.2	1.4	3.0	0.2	0.2	0	65.6	65.6	2	LG	S	S	3	B	S	S
600c	6.4	6.9	1.6	0.2	-	-	57.3	57.3	1	LG	S	S	3	B	S	S
Temperature 2100°F																
4	2.0	2.1	0.2	0.1	0.1	0	63.9	79.0	6	LG	S	S	2	B	S	W
16	3.4	1.2	0.2	0.3	0.1	0	62.6	73.9	4	LG	S	S	2	B	P	W
64	4.2	2.5	0.4	0.3	0.15	0	64.6	65.9	1	LG	S	S	2	B	P	W
100	10.8	9.2	1.6	0.5	0.25	0	63.4	65.0	1	LG	S	S	3	B	P	S
200	17.7	16.0	1.5	0.2	0.4	0	51.9	51.9	1	LG	S	S	3	B	P	S
300	14.3	10.2	2.1	0.4	0.3	0	62.0	63.0	1	G	S	S	3	B	P	S
400	14.3	9.9	2.0	0.2	-	0	64.9	65.8	1	G	S	S	3	B	P	S
500	21.4	15.5	3.3	0.6	0.6	0	62.9	63.2	1	G	S	S	3	B	P	S
600	20.8	18.8	6.5	0.7	1.0	0	60.7	60.7	1	G	S	S	3	B	P	S
600c	33.5	30.3	5.0	0.7	-	-	53.1	53.1	1	G	S	S	3	B	P	S
Temperature 2200°F																
4	2.8	1.7	0.5	0.3	0.1	0	65.5	82.1	7	LG	S	S	2	B	P	W
16	4.9	1.2	0.4	0.5	0.15	0	66.9	71.5	1	LG	S	S	2	B	P	W
64	10.2	-	0.8	0.5	0.4	0	50.0	50.0	1	LG	S	S	2	B	P	S
100	17.2	17.3	1.7	0.4	0.5	0	45.7	45.7	1	LG	S	S	3	B	P	S
200	28.9	35.3	3.8	0.7	0.7	0	59.0	59.0	1	LG	S	S	3	B	P	S
300	26.6	30.4	3.4	0.3	1.0	0	61.8	61.8	1	LG	S	S	3	B	P	S
400	30.4	29.3	2.9	0.1	-	0	44.7	44.7	1	LG	S	S	3	B	P	S
500	42.0	41.5	2.4	0.1	-	0	43.2	43.2	1	LG	S	S	3	B	P	S
600	57.5	48.4	12.8	-0.2	1.2	0	-	-	-	LG	S	S	3	B	P	S
600c	43.2	29.2	10.8	-0.3	-	-	42.5	42.5	1	LG	S	S	3	B	P	S

TABLE A1-9 NUMERICAL DATA TABULATION: ALLOY 9, RA 333.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.4	0.4	0.0	0.2	0	0	37.1	89.7	49	IC	S	ND	ND	–	–	ND
16	0.5	0.6	0.0	0.0	0	0	38.8	92.8	41	GB	S	ND	ND	–	–	ND
64	0.7	0.5	0.0	0.1	0	0	40.3	92.3	38	GB	S	ND	ND	–	–	ND
100	0.8	0.7	0.0	0.2	0	0	40.7	94.5	36	GB	S	ND	ND	–	–	ND
200	1.2	0.8	0.0	0.3	0.05	0	39.4	89.6	35	GB	S	ND	ND	–	–	ND
300	1.5	1.4	0.0	0.4	0.05	0	38.7	92.5	29	GB	S	ND	ND	–	–	ND
400	1.4	1.1	0.0	0.3	0.1	0	39.4	94.0	32	GB	S	ND	ND	–	–	ND
500	1.6	1.6	0.0	0.4	0.15	0	38.2	88.5	29	GB	S	ND	ND	–	–	ND
600	1.9	1.9	0.1	0.2	0.1	0	37.5	91.3	35	GB	S	ND	1	B	P	ND
600c	1.8	1.8	0.1	0.2	–	–	36.2	87.0	30	GB	S	ND	1	B	P	ND
Temperature 1600°F																
4	0.8	0.1	0.0	0.0	<0.05	0.05	36.7	88.1	36	B	S	ND	1	B	P	ND
16	1.6	1.8	0.0	0.2	0.15	0.45	36.4	89.5	43	B	F	ND	1	B	P	ND
64	2.1	2.5	0.6	0.4	0.15	–	35.3	86.0	33	B	F	ND	2	B	P	ND
100	2.4	3.3	0.6	0.4	0.15	0.35	36.8	94.6	40	B	P	ND	2	B	P	ND
200	2.9	3.6	1.6	0.3	0.2	–	34.3	92.7	37	B	P	ND	3	B	P	ND
300	3.7	4.5	1.9	0.1	0.2	0.5	35.4	89.0	36	B	P	ND	3	B	P	ND
400	3.7	4.6	1.5	0.1	0.2	0.5	36.1	92.4	37	B	P	ND	3	B	P	ND
500	4.7	5.8	3.5	0.6	0.3	0.8	35.2	94.0	38	B	P	ND	3	B	P	ND
600	4.7	5.6	3.8	0.3	0.4	–	37.0	95.3	37	B	P	ND	3	B	P	ND
600c	4.9	6.0	4.5	0.2	–	–	36.6	93.7	37	B	P	ND	3	B	P	ND
Temperature 1800°F																
4	1.0	2.2	3.7	0.4	0.1	0.1	38.8	94.7	43	IC	F	ND	3	B	S	W
16	2.4	4.2	4.6	0.3	0.2	0.2	32.8	92.2	42	G	P	ND	3	B	S	W
64	1.7	4.2	4.7	0.3	0.2	0.5	35.1	92.5	45	G	P	ND	3	B	S	W
100	5.1	7.1	6.6	0.8	–	–	34.4	88.0	42	G	P	ND	3	B	S	W
200	7.2	8.7	14.4	0.8	–	0.8	32.2	87.1	41	G	P	ND	3	B	S	W
300	8.3	10.0	18.3	1.0	–	1.9	32.5	88.7	44	G	P	ND	4	B	S	W
400	11.9	13.6	23.5	1.3	0.8	2.9	28.1	83.1	43	G	P	ND	4	B	S	W
500	12.8	14.7	24.3	2.3	0.8	5.3	32.0	82.5	45	G	P	ND	4	B	S	W
600	12.9	16.3	28.8	1.0	0.8	3.1	30.7	81.5	43	G	P	ND	4	B	S	W
600c	14.4	15.4	30.2	1.4	–	–	34.0	90.6	43	G	P	ND	4	B	S	W

TABLE A1-9 NUMERICAL DATA TABULATION: ALLOY 9, RA 333.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in^2		WEIGHT GAIN & THICKNESS CHANGE				MECHANICAL PROPERTIES			METAL STRIP			SPALL			
	DIR.	INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	5.3	6.7	8.4	1.4	0.1	0.6	34.6	87.9	49	IC	F	ND	3	B	S	W
16	9.8	12.3	26.7	1.3	0.5	1.5	34.1	86.0	50	LG	F	ND	4	B	S	W
64	8.1	10.3	20.9	1.1	0.3	-	32.7	88.0	51	G	P	ND	4	B	S	W
100	11.6	15.9	27.4	1.6	0.5	-	29.6	82.1	48	G	P	ND	4	B	S	W
200	20.8	23.5	46.0	1.6	0.5	-	31.1	85.4	40	G	P	ND	4	B	S	W
300	27.5	32.4	71.2	2.4	1.0	7.0	33.3	80.3	42	G	P	ND	4	B	S	W
400	29.4	32.6	70.7	2.4	1.0	8.5	32.4	80.6	41	G	P	ND	4	B	S	W
500	35.5	38.4	20.0	3.4	1.3	-	30.0	74.8	42	G	P	ND	4	B	S	W
600	50.6	41.1	130.0	3.4	1.5	7.0	30.6	77.4	43	G	P	ND	4	B	S	W
600c	41.6	52.7	108.1	3.5	-	-	30.1	72.3	41	G	P	ND	4	B	S	W
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																

TABLE A1-10 NUMERICAL DATA TABULATION: ALLOY 10, HASTELLOY X.

EXPOSURE TIME HOURS	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC SPALL WEIGHT mg/in2	WEIGHT GAIN & THICKNESS CHANGE: THICKNESS CHANGE 10^{-3} in	WEIGHT GAIN & THICKNESS CHANGE: AVERAGE OXIDE THICKNESS 10^{-3} in	WEIGHT GAIN & THICKNESS CHANGE: MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	MECHANICAL PROPERTIES: ULTIMATE STRENGTH 10^3 psi	MECHANICAL PROPERTIES: ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	METAL STRIP: TEXTURE	METAL STRIP: MAGNETIC PROPERTIES	SPALL: AMOUNT	SPALL: COLOR	SPALL: PARTICLE SIZE	SPALL: MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.4	0.4	0.0	0.2	–	0	40.6	78.7	18	IC	S	ND	ND	–	–	–
16	0.5	0.5	0.0	0.1	–	0	42.7	75.8	15	G	S	ND	ND	–	–	–
64	0.6	0.6	0.0	0.2	<0.05	0	43.4	74.8	12	G	S	ND	ND	–	–	–
100	0.8	0.7	0.0	0.3	0.05	0	42.9	81.0	16	G	S	ND	ND	–	–	–
200	1.0	15.0	0.0	0.4	0.05	0	44.4	84.9	14	BlB	S	ND	ND	–	–	–
300	1.0	0.8	0.0	0.1	0.05	0	45.1	83.2	13	BlB	S	ND	ND	–	–	–
400	1.2	0.8	0.0	0.2	0.05	0	46.0	85.8	11	BlB	S	ND	ND	–	–	–
500	1.3	1.2	0.0	0.4	0.05	0	45.6	81.3	10	BlB	S	ND	ND	–	–	–
600	1.5	1.4	0.1	0.3	0.05	0	46.6	81.3	6	BlB	S	ND	ND	–	–	–
600c	1.4	1.2	0.0	0.2	–	–	46.3	83.7	10	BlB	S	ND	ND	–	–	–
Temperature 1600°F																
4	0.6	0.6	0.0	0.1	0	0	43.1	82.6	17	Gr	P	ND	1	B	P	W
16	1.6	1.5	0.0	0.2	<0.1	0	43.8	86.8	16	GGr	P	ND	1	B	P	W
64	1.5	1.9	0.1	0.5	0.1	0	45.3	93.0	13	GGr	P	ND	1	B	P	W
100	1.9	2.2	0.1	0.4	0.1	0	46.6	94.3	15	GB	P	ND	1	B	P	W
200	2.4	2.6	0.1	0.4	0.15	0	47.9	93.8	11	GB	P	ND	1	B	P	W
300	2.8	3.4	0.2	0.3	0.1	0	47.5	96.0	11	GB	P	ND	2	B	P	W
400	3.3	3.7	0.5	0.3	0.1	0	46.9	92.7	9	GB	P	ND	2	B	P	W
500	3.5	4.1	0.7	0.6	0.15	0	45.4	98.7	11	GB	P	ND	2	B	P	W
600	1.2	4.6	3.4	0.4	0.2	0	46.9	94.0	9	GB	P	ND	2	B	P	W
600c	3.8	4.4	0.8	0.5	–	–	46.6	92.8	9	GB	P	ND	2	B	P	W
Temperature 1800°F																
4	1.0	1.6	0.4	0.3	0.05	0	42.3	98.5	28	GGr	FP	ND	2	GrB	M	W
16	1.1	2.6	1.7	0.3	0.1	0.2	40.3	99.3	28	GGr	FP	ND	2	GrB	M	W
64	2.5	3.5	0.8	0.4	0.2	0.6	45.9	99.3	17	Gr	FP	ND	2	GrB	M	W
100	3.6	4.7	0.8	0.6	0.2	0.6	42.5	97.2	21	G	P	ND	2	GrB	M	W
200	6.5	8.4	2.2	1.2	–	1.0	41.4	93.0	16	GB	P	ND	3	GrB	M	W
300	7.7	8.9	1.6	1.3	–	1.2	39.4	89.3	21	BrB	P	ND	3	GrB	M	W
400	9.2	11.1	1.7	1.8	0.4	1.2	38.9	79.8	14	BrB	P	ND	3	GrB	M	W
500	8.8	10.6	1.4	1.4	0.4	1.2	38.8	83.7	16	BrB	P	ND	2	GrB	M	W
600	11.1	15.0	1.9	2.0	0.6	3.2	38.1	84.7	18	BrB	P	ND	3	GrB	M	W
600c	13.1	12.5	2.4	2.5	–	–	38.0	88.3	19	BrB	P	ND	3	GrB	M	W

TABLE A1-10 NUMERICAL DATA TABULATION: ALLOY 10, HASTELLOY X.

EXPOSURE TIME HOURS	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in²	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	2.4	4.0	1.0	0.5	0.1	0.4	41.9	99.5	33	Gr	P	ND	2	B	P	W
16	6.0	7.5	1.0	1.7	0.2	0.6	39.8	98.1	30	Gr	P	ND	2	B	P	W
64	11.8	12.7	2.3	2.0	0.2	0.9	39.9	91.6	30	Gr	P	ND	3	B	P	W
100	13.8	14.2	4.2	2.8	0.3	1.8	38.3	88.8	28	GBr	P	ND	3	B	P	W
200	19.2	22.1	17.8	3.1	0.3	1.7	37.1	86.5	28	GBr	L	ND	4	B	P	W
300	19.8	24.4	25.9	3.5	-	3.0	36.4	84.8	29	GBr	L	ND	4	B	P	W
400	18.5	398.5	33.3	3.3	-	5.0	37.6	85.4	25	GBr	L	ND	4	B	P	W
500	-	-	-	3.3	-	6.0	36.9	85.3	27	GBr	L	ND	-	B	P	W
600	13.0	31.3	40.2	2.6	1.4	5.3	37.7	85.7	28	GBr	L	ND	4	B	P	W
600c	27.3	27.9	53.9	2.2	-	-	36.6	83.8	25	GBr	L	ND	4	B	P	W
Temperature 2100°F																
4	6.3	7.1	1.3	0.7	0.1	-	38.2	95.3	29	Gr	F	ND	2	B	P	W
16	9.2	10.0	1.4	1.3	0.2	-	35.7	96.0	31	Br	F	ND	3	B	P	W
64	13.1	14.5	7.6	2.4	0.2	-	35.3	90.5	24	Br	L	ND	3	B	P	W
100	15.0	18.0	14.8	2.7	0.3	-	34.8	89.6	31	Br	L	ND	4	B	P	W
200	11.8	20.9	25.7	2.2	-	-	30.2	93.1	36	Br	L	ND	4	B	P	W
300	15.8	24.8	41.8	2.1	-	-	37.0	87.9	34	Br	L	ND	4	B	P	W
400	1.0	27.7	40.7	2.2	-	-	33.6	88.5	38	Br	L	ND	4	B	P	W
500	14.7	27.8	53.2	2.4	-	-	34.0	86.7	33	Br	L	ND	4	B	P	W
600	0.9	31.0	55.2	2.9	1.4	-	35.2	86.5	34	Br	L	ND	4	B	P	W
600c	7.9	38.0	55.4	2.5	-	-	35.6	85.9	34	Br	L	ND	4	B	P	W
Temperature 2200°F																
4	7.1	8.7	2.9	1.0	0.1	-	36.0	98.5	43	Gr	F	ND	3	B	P	W
16	9.9	11.8	5.0	1.1	0.4	-	40.9	104.0	49	Br	L	ND	3	B	P	W
64	11.8	17.4	16.3	1.9	-	-	41.2	104.1	38	Br	L	ND	4	B	P	W
100	10.4	20.7	23.5	2.0	-	-	37.7	94.4	48	Br	L	ND	4	B	P	W
200	14.4	34.6	57.0	2.1	-	-	38.9	95.4	39	Br	L	ND	4	B	L	W
300	55.7	65.7	154.7	3.4	-	-	37.7	88.0	37	Br	L	ND	5	B	L	W
400	15.3	38.5	99.0	2.1	-	-	38.4	90.3	39	Br	L	ND	4	B	L	W
500	54.4	94.4	250.8	3.5	-	-	34.6	69.3	8	Br	L	ND	5	B	L	W
600	125.9	153.8	644.1	3.2	1.6	-	31.9	81.3	36	Br	L	ND	5	B	L	W
600c	165.7	192.1	816.4	4.3	-	-	29.5	69.1	19	Br	L	ND	5	B	L	w

TABLE A1-11 . NUMERICAL DATA TABULATION: ALLOY 11, UDIMET 500.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in2 DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in2 INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP COLOR	METAL STRIP TEXTURE	METAL STRIP MAGNETIC PROPERTIES	SPALL AMOUNT	SPALL COLOR	SPALL PARTICLE SIZE	SPALL MAGNETIC PROPERTIES
	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.4	0.5	0.0	0.0	0	0	95.6	164.6	18	G	S	ND	ND	–	–	–
16	0.5	0.7	0.0	0.2	0	0	99.3	162.0	14	G	S	ND	ND	–	–	–
64	0.9	0.8	0.0	0.2	0	0	93.0	149.4	9	G	S	ND	ND	–	–	–
100	0.8	2.2	0.0	0.1	<0.05	0.15	98.4	154.2	10	G	S	ND	ND	–	–	–
200	1.4	1.0	0.0	0.4	0.1	0.7	110.0	155.9	9	G	S	ND	ND	–	–	–
300	1.5	1.3	0.0	0.1	0.3	0.4	91.6	134.2	13	G	S	ND	ND	–	–	–
400	2.1	1.8	0.0	0.2	–	–	105.0	157.2	8	G	S	ND	ND	–	–	–
500	1.6	1.5	0.0	0.2	0.3	0.4	95.4	153.3	7	G	S	ND	ND	–	–	–
600	2.1	2.5	0.1	0.4	0.3	0.4	112.2	158.0	9	G	S	ND	ND	–	–	–
600c	2.6	1.8	0.0	0.2	–	–	87.8	142.6	6	G	S	ND	ND	–	–	–
Temperature 1600°F																
4	1.3	1.3	0.0	0.3	0.05	0.15	84.6	130.1	6	G	S	ND	ND	–	–	–
16	2.1	1.9	0.0	0.4	0.05	0.15	66.6	151.5	13	G	S	ND	1	B	P	ND
64	3.6	3.7	0.0	0.4	0.1	0.35	84.8	133.9	7	G	S	ND	1	B	P	ND
100	4.4	4.5	0.0	0.5	0.1	0.5	77.9	146.0	10	G	S	ND	1	B	P	ND
200	5.6	5.6	0.0	0.5	–	0.7	82.7	148.6	12	G	S	ND	1	B	P	ND
300	6.6	6.9	0.0	0.2	–	1.1	89.7	139.0	10	G	S	ND	1	B	P	ND
400	7.7	7.9	0.0	0.6	–	1.1	92.0	152.5	13	G	S	ND	1	B	P	ND
500	7.9	8.0	0.2	0.5	–	1.2	89.5	151.5	12	G	S	ND	1	B	P	ND
600	8.6	9.0	0.2	0.6	0.8	1.3	75.4	142.3	12	G	S	ND	1	B	P	ND
600c	8.8	–	0.2	0.8	–	–	87.9	150.3	12	G	S	ND	1	B	P	ND
Temperature 1800°F																
4	4.1	4.9	1.6	0.6	0.2	0.6	89.0	116.8	8	GGr	L	ND	3	B	P	ND
16	6.4	6.7	1.6	0.7	0.2	0.7	80.2	115.8	8	GGr	L	ND	3	B	P	ND
64	8.3	8.7	1.0	0.9	0.3	1.3	78.2	88.5	4	GGr	L	ND	2	B	P	ND
100	11.5	–	2.9	1.3	–	1.5	72.8	111.0	7	GGr	L	ND	3	B	P	ND
200	11.6	17.9	5.1	1.3	–	1.5	67.2	68.2	1	GGr	L	ND	3	B	P	W
300	18.6	19.8	6.3	1.3	–	2.8	68.7	75.9	1	GGr	L	ND	3	B	P	W
400	21.9	24.2	14.3	1.2	–	3.5	72.0	86.6	2	GGr	L	ND	3	B	P	W
500	21.5	22.9	11.5	1.2	1.5	1.5	61.6	72.4	2	GGr	L	ND	3	B	P	W
600	22.8	28.6	16.6	1.6	1.5	1.5	72.8	78.7	1	GGr	L	ND	4	B	P	W
600c	26.1	26.2	28.9	1.4	–	–	75.6	92.0	2	GGr	L	ND	4	B	P	W

TABLE A1-11 NUMERICAL DATA TABULATION: ALLOY 11, UDIMET 500.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in² DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in² INDIR.	SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP COLOR	METAL STRIP TEXTURE	METAL STRIP MAGNETIC PROPERTIES	SPALL - AMOUNT	SPALL - COLOR	SPALL - PARTICLE SIZE	SPALL - MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	9.5	10.3	3.1	0.9	0.2	1.2	94.2	156.8	20	G	L	ND	3	B	P	ND
16	12.1	14.5	9.7	1.4	0.3	1.7	79.9	155.1	25	G	L	ND	3	B	P	W
64	17.2	20.5	33.4	1.4	0.3	0.8	93.7	152.5	27	GGr	L	ND	4	B	P	W
100	16.1	19.0	50.1	1.0	-	0.9	81.9	153.4	30	GGr	L	ND	4	B	P	W
200	23.0	25.9	91.8	0.4	-	-	87.8	159.5	30	GBl	L	ND	4	B	P	W
300	18.5	20.5	-	0.4	-	-	88.3	157.3	31	GBl	L	ND	4	B	P	W
400	25.3	26.4	96.0	0.2	-	-	89.0	158.1	29	GBl	L	ND	4	B	P	W
500	26.9	26.3	108.4	0.6	1.5	-	95.8	156.1	26	GBl	L	ND	4	B	P	W
600	26.9	26.1	109.7	0.1	1.5	-	92.4	154.2	32	GBl	L	ND	4	B	P	W
600c	29.4	23.5	114.0	0.0	-	-	91.4	154.4	32	GBl	L	ND	4	B	P	W
Temperature 2100°F																
4	14.5	15.8	4.8	1.0	0.3	1.1	88.5	142.1	25	G	F	ND	3	B	P	W
16	22.3	23.7	15.7	1.5	0.5	1.3	84.0	157.3	29	G	F	ND	4	B	P	W
64	30.3	33.5	112.6	-0.5	-	-	91.5	150.0	25	Bl	F	ND	4	GB	P	W
100	33.0	35.1	130.2	-0.1	-	-	96.2	157.9	35	Bl	P	ND	4	B	P	W
200	53.5	55.1	214.0	-0.8	-	1.1	86.0	148.8	34	Bl	L	ND	5	B	P	W
300	62.7	60.4	259.9	-0.8	-	1.8	77.5	145.2	31	Bl	L	ND	5	B	P	W
400	81.3	82.0	340.7	-1.1	-	-	82.8	142.8	36	Bl	L	ND	5	B	P	W
500	104.8	99.9	465.1	-1.2	-	-	76.7	130.0	31	Bl	L	ND	5	B	P	W
600	138.4	136.9	563.9	-2.2	2.0	-	69.4	123.9	32	Bl	L	W	5	B	P	W
600c	133.4	122.3	525.6	-2.3	-	-	72.5	125.0	32	Bl	L	W	5	B	P	W
Temperature 2200°F																
4	15.2	17.0	17.3	1.0	0.3	0.5	95.5	159.7	31	G	L	W	4	B	P	W
16	27.0	30.3	9.9	0.5	0.4	-	94.9	157.0	31	G	L	W	4	B	P	W
64	54.7	58.4	172.7	0.5	0.2	1.5	84.6	143.7	32	Gr	L	W	5	B	P	W
100	66.8	74.3	276.7	0.5	-	-	83.7	144.8	32	Gr	L	W	5	B	P	W
200	135.2	140.0	520.0	-0.6	-	-	60.5	117.5	30	Bl	L	W	5	B	P	W
300	233.4	239.0	922.7	-2.7	-	-	60.4	116.2	24	Bl	L	W	5	B	P	W
400	281.8	287.8	-	-2.8	-	-	53.8	98.7	27	Bl	L	W	5	B	P	W
500	342.5	336.3	1402.9	-3.4	-	-	39.5	79.4	30	Bl	L	S	5	B	P	W
600	460.1	463.1	1910.7	-5.7	5.0	-	30.6	60.8	26	Bl	L	S	6	B	P	W
600c	447.5	51.1	1902.5	-5.8	-	-	29.9	63.5	26	Bl	L	S	6	B	P	W

TABLE A1-12 NUMERICAL DATA TABULATION: ALLOY 12, HAYNES 25.

EXPOSURE TIME HOURS	SPECIFIC TOTAL WEIGHT GAIN mg/in2		SPECIFIC SPALL WEIGHT mg/in2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	COLOR	TEXTURE	MAGNETIC PROPERTIES	AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
	WEIGHT GAIN & THICKNESS CHANGE						MECHANICAL PROPERTIES			METAL STRIP			SPALL			
	DIR.	INDIR.														
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 1400°F																
4	0.3	0.3	0.0	0.1	0	0	57.6	127.3	53	IC	S	ND	ND	-	-	-
16	0.5	0.5	0.1	0.1	0	0	57.2	120.3	46	IC	S	ND	ND	-	-	-
64	0.5	0.5	0.0	0.2	0	0	52.7	110.0	29	IC	S	ND	ND	-	-	-
100	0.5	0.6	0.0	0.2	0	0	55.2	112.9	33	IC	S	ND	ND	-	-	-
200	0.9	0.6	0.0	0.0	0	0	59.5	99.4	18	Gr	S	ND	ND	-	-	-
300	0.7	0.9	0.0	0.3	0	0	59.8	120.0	22	Gr	S	ND	ND	-	-	-
400	1.0	0.9	0.0	0.2	0.05	0	54.7	97.6	16	Gr	S	ND	ND	-	-	-
500	0.9	1.0	0.0	0.2	0.05	0	65.0	113.7	16	Gr	S	ND	ND	-	-	-
600	1.1	1.6	0.0	0.1	0.05	0	54.8	96.8	12	Gr	S	ND	ND	-	-	-
600c	1.4	-	0.0	0.1	-	-	70.5	107.0	13	Gr	S	ND	ND	-	-	-
Temperature 1600°F																
4	0.6	0.6	0.0	0.2	0	0	55.6	114.0	33	Gr	S	ND	1	Gr	M	ND
16	1.1	1.2	0.0	0.2	0	0	50.7	109.0	31	Gr	S	ND	1	B	S	ND
64	1.9	2.0	0.0	0.2	0.1	0.2	57.0	102.0	16	Gr	S	ND	1	B	S	ND
100	2.0	2.0	0.0	0.3	0.1	-	52.0	103.8	17	Gr	S	ND	1	B	S	ND
200	3.0	2.9	0.1	0.3	0.2	0.4	57.1	107.4	11	Gr	S	ND	1	B	S	ND
300	3.0	3.6	0.1	0.1	0.2	0.7	57.1	106.8	12	Gr	S	ND	1	B	S	ND
400	3.7	3.9	0.1	0.6	0.2	-	58.0	110.5	8	Gr	S	ND	1	B	S	ND
500	3.6	3.7	0.2	0.4	0.2	-	57.6	111.2	11	Gr	S	ND	1	B	S	ND
600	4.3	4.5	0.3	0.5	0.2	0.4	64.5	120.4	8	Gr	S	ND	1	B	S	ND
600c	4.1	4.3	0.1	0.3	-	-	55.0	109.9	6	Gr	S	ND	1	B	S	ND
Temperature 1800°F																
4	7.7	7.7	0.1	0.7	0.1	0	51.0	116.1	38	G	F	ND	1	B	S	ND
16	8.0	8.0	0.1	0.9	0.15	0	57.8	98.3	18	G	F	ND	1	B	S	ND
64	8.3	8.4	0.2	0.8	0.2	0	63.6	118.2	17	G	F	ND	2	B	S	ND
100	8.0	8.3	0.1	1.0	0.2	0	63.0	120.5	12	G	F	ND	1	B	S	ND
200	16.8	-	1.3	1.5	0.5	1.0	56.3	116.8	7	G	F	ND	2	B	S	ND
300	12.3	-	1.3	1.5	0.3	-	55.8	111.0	8	G	F	ND	2	B	S	ND
400	12.9	14.2	1.3	1.3	0.4	1.9	57.1	106.1	7	G	F	ND	2	B	S	ND
500	14.1	14.7	2.1	1.5	0.6	-	55.1	102.7	3	G	F	ND	3	B	S	ND
600	12.5	22.5	0.8	1.3	0.6	2.4	50.3	99.7	6	G	F	ND	3	B	S	W
600c	21.7	12.9	8.2	2.0	-	-	58.0	111.7	6	G	F	ND	2	B	S	W

TABLE A1-12 NUMERICAL DATA TABULATION: ALLOY 12, HAYNES 25.

EXPOSURE TIME HOURS	WEIGHT GAIN & THICKNESS CHANGE: SPECIFIC TOTAL WEIGHT GAIN mg/in^2 DIR.	SPECIFIC TOTAL WEIGHT GAIN mg/in^2 INDIR.	SPECIFIC SPALL WEIGHT mg/in^2	THICKNESS CHANGE 10^{-3} in	AVERAGE OXIDE THICKNESS 10^{-3} in	MAX DEPTH OF PENETRATION 10^{-3} in	MECHANICAL PROPERTIES: YIELD STRENGTH 10^3 psi	ULTIMATE STRENGTH 10^3 psi	ELONGATION PERCENTAGE 1.0 in	METAL STRIP: COLOR	TEXTURE	MAGNETIC PROPERTIES	SPALL: AMOUNT	COLOR	PARTICLE SIZE	MAGNETIC PROPERTIES
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Temperature 2000°F																
4	11.4	11.6	0.5	0.8	0.5	-	53.8	120.0	43	G	F	ND	2	B	S	ND
16	12.6	13.1	0.3	1.4	0.7	1.7	51.0	119.0	37	G	F	ND	2	B	S	ND
64	17.9	18.9	6.0	1.6	0.9	2.9	46.2	110.5	26	G	F	ND	3	B	S	W
100	16.3	17.2	4.0	1.5	0.9	3.4	45.2	109.0	24	G	L	ND	3	B	S	W
200	31.0	33.7	51.7	1.8	-	-	47.8	101.5	21	G	L	ND	4	B	M	W
300	47.1	49.5	87.4	5.1	-	-	44.7	105.5	19	G	L	W	4	B	M	W
400	108.2	119.0	314.0	4.7	-	4.0	39.1	91.6	18	G	L	W	5	B	M	W
500	122.4	123.5	366.4	1.8	1.5	-	46.1	98.5	17	G	L	W	5	B	M	W
600	175.7	233.8	725.0	-4.7	1.5	-	42.4	92.8	20	G	L	W	5	B	M	W
600c	229.1	191.7	925.3	-3.7	-	-	50.1	94.3	18	G	L	W	5	B	M	W
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																
Temperature °F																
4																
16																
64																
100																
200																
300																
400																
500																
600																
600c																

APPENDIX 2
ALLOY OXIDATION PLOTS

CONTENTS

SPECIFIC TOTAL OXIDATION WEIGHT GAIN

ALLOY	FIGURE	PAGE
1. N 155	A2-1	70
2. TD nickel	A2-2	71
3. TD nickel-chromium	A2-3	72
4. Bendel 65-35	A2-4	73
5. Chromel A.	A2-5	74
6. DH 242	A2-6	75
7. GE 1541	A2-7	76
8. Hoskins 875	A2-8	77
9. RA 333	A2-9	78
10. Hastelloy X.	A2-10	79
11. Udimet 500	A2-11	80
12. Haynes 25	A2-12	81

SPECIFIC OXIDE SPALL WEIGHT

ALLOY	FIGURE	PAGE
1. N 155	A2-13	82
2. TD nickel	A2-14	83
3. TD nickel-chromium	A2-15	84
4. Bendel 65-35	A2-16	85
5. Chromel A.	A2-17	86
6. DH 242	A2-18	87
7. GE 1541	A2-19	88
8. Hoskins 875	A2-20	89
9. RA 333	A2-21	90
10. Hastelloy X.	A2-22	91
11. Udimet 500	A2-23	92
12. Haynes 25	A2-24	93

Specific total oxidation weight gain and specific oxide spall weight are plotted for each alloy as a function of exposure time with temperature as a parameter. Power function plots on a log-log grid were linear for most data.

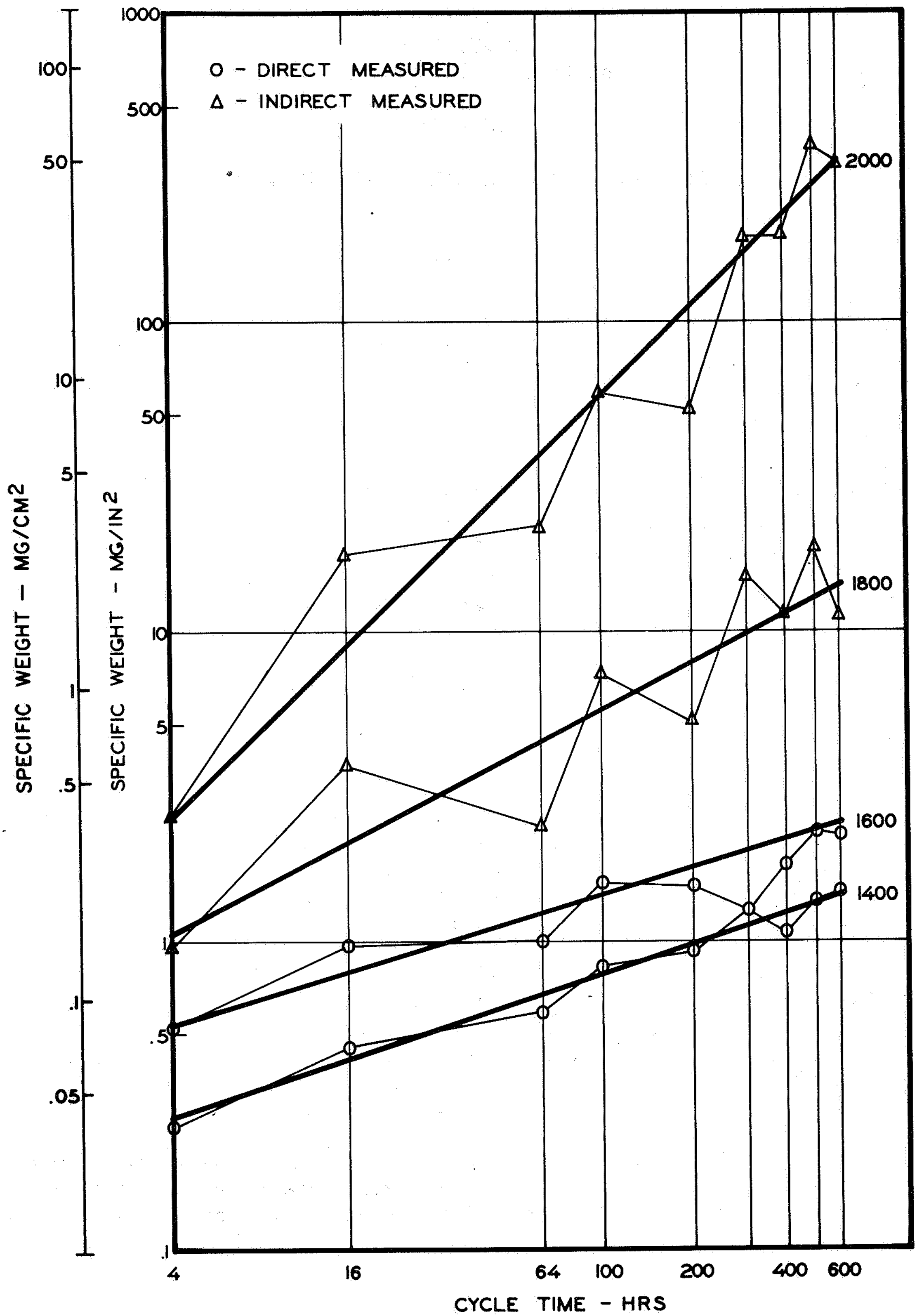


Figure A2-1 Specific total oxidation weight gain: Alloy 1, N 155.

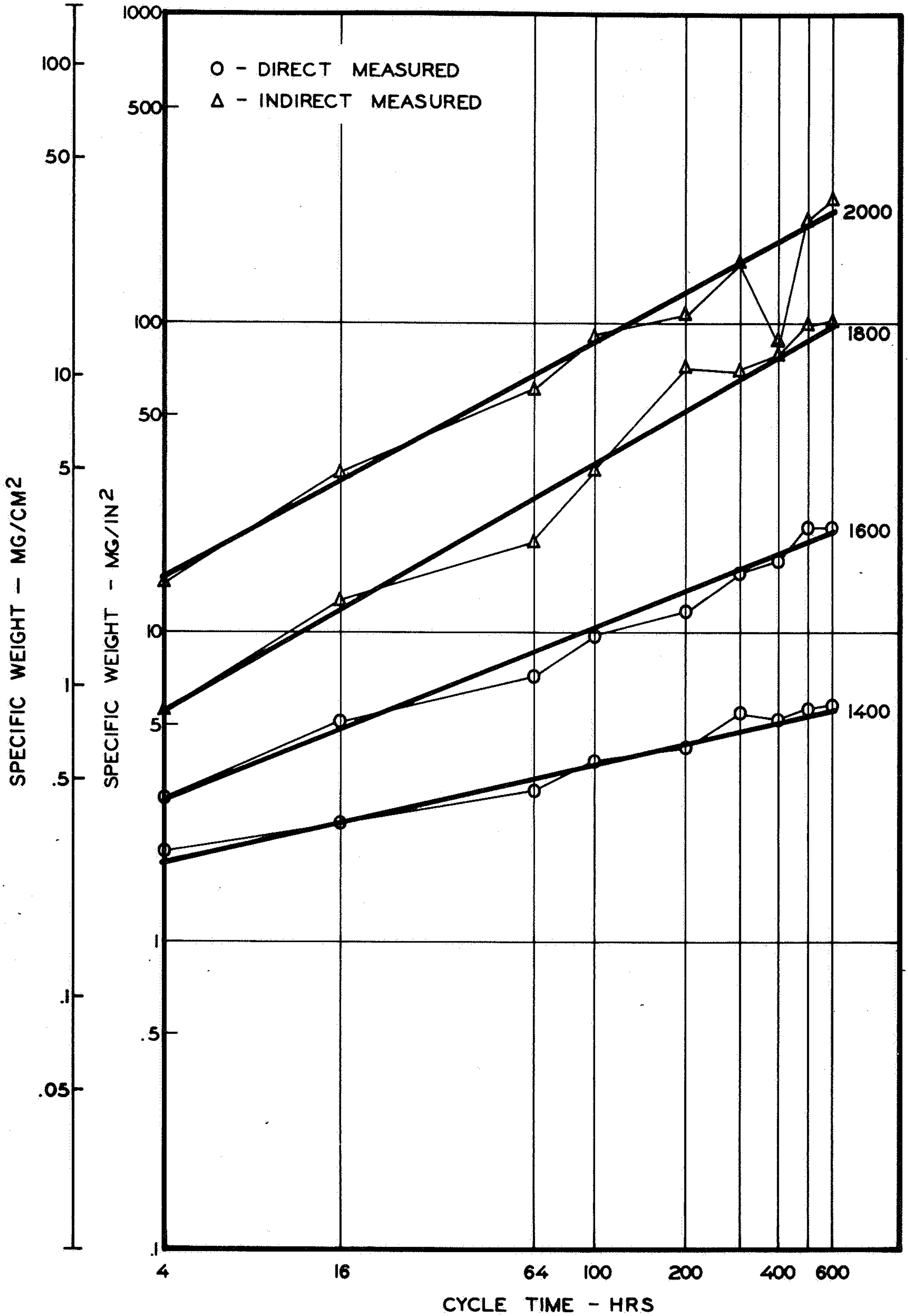


Figure A2-2 Specific total oxidation weight gain: Alloy 2, TD nickel.

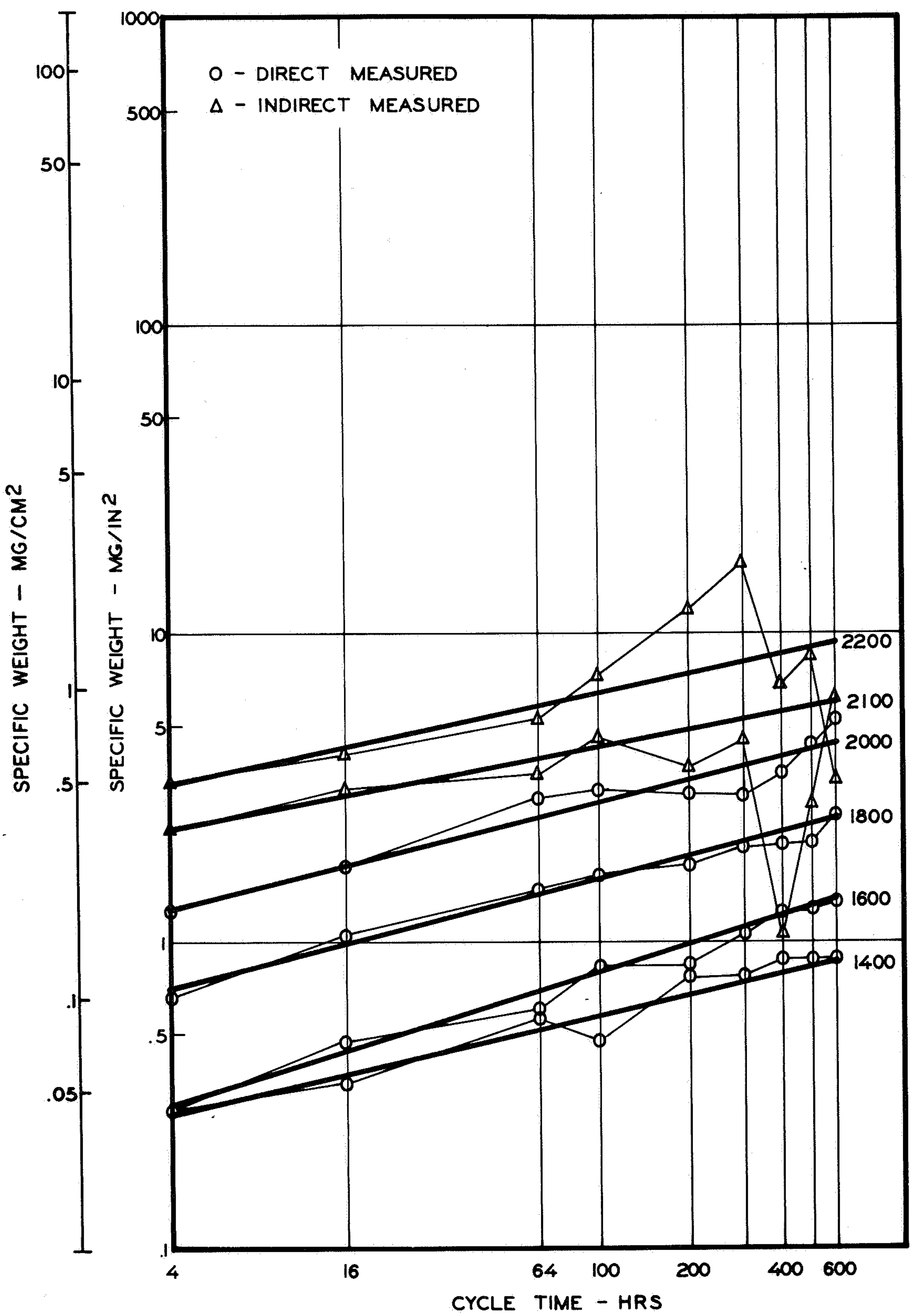


Figure A2-3 Specific total oxidation weight gain: Alloy 3, TD nickel-chromium.

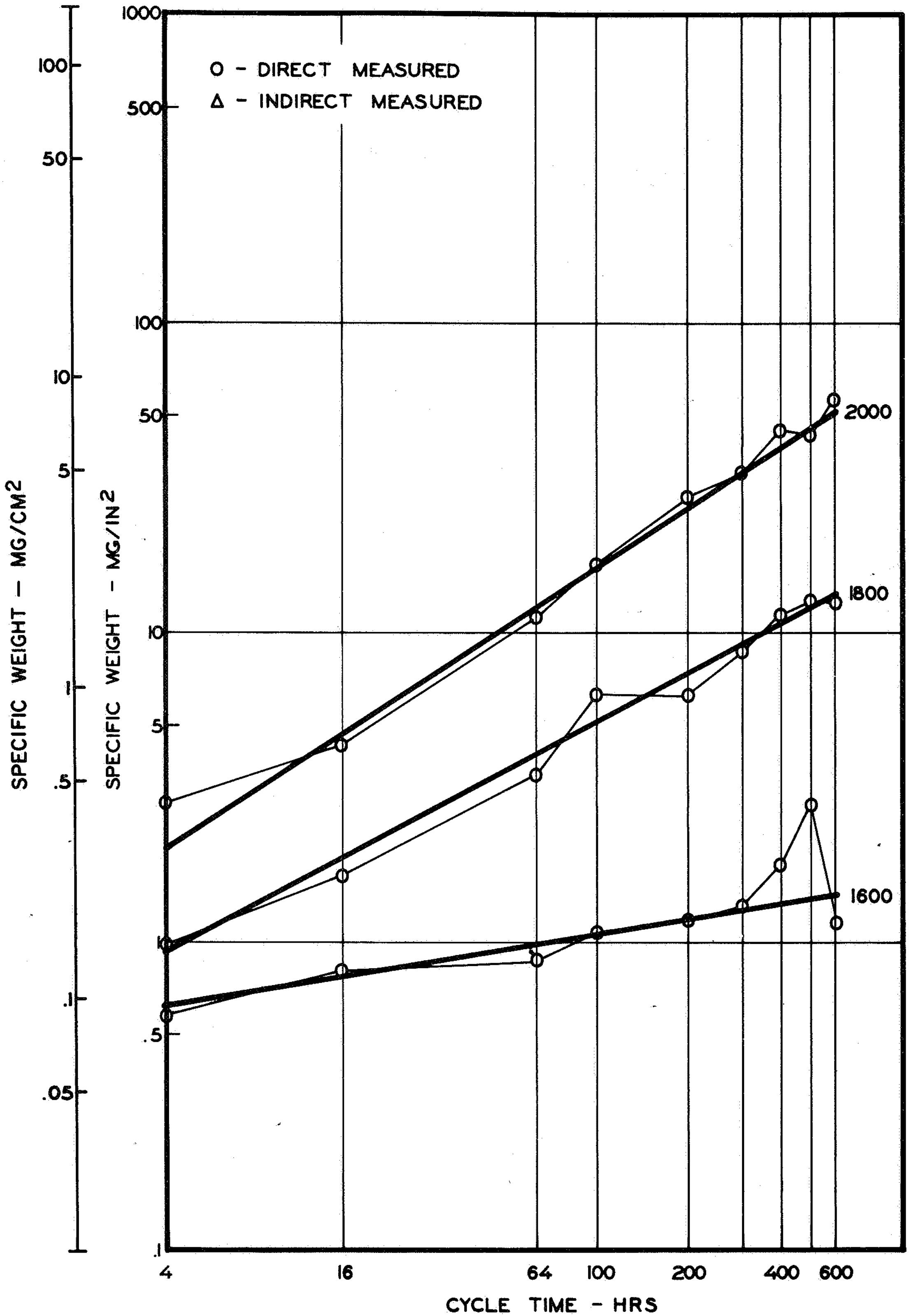


Figure A2-4 Specific total oxidation weight gain: Alloy 4, Bendel 65-35.

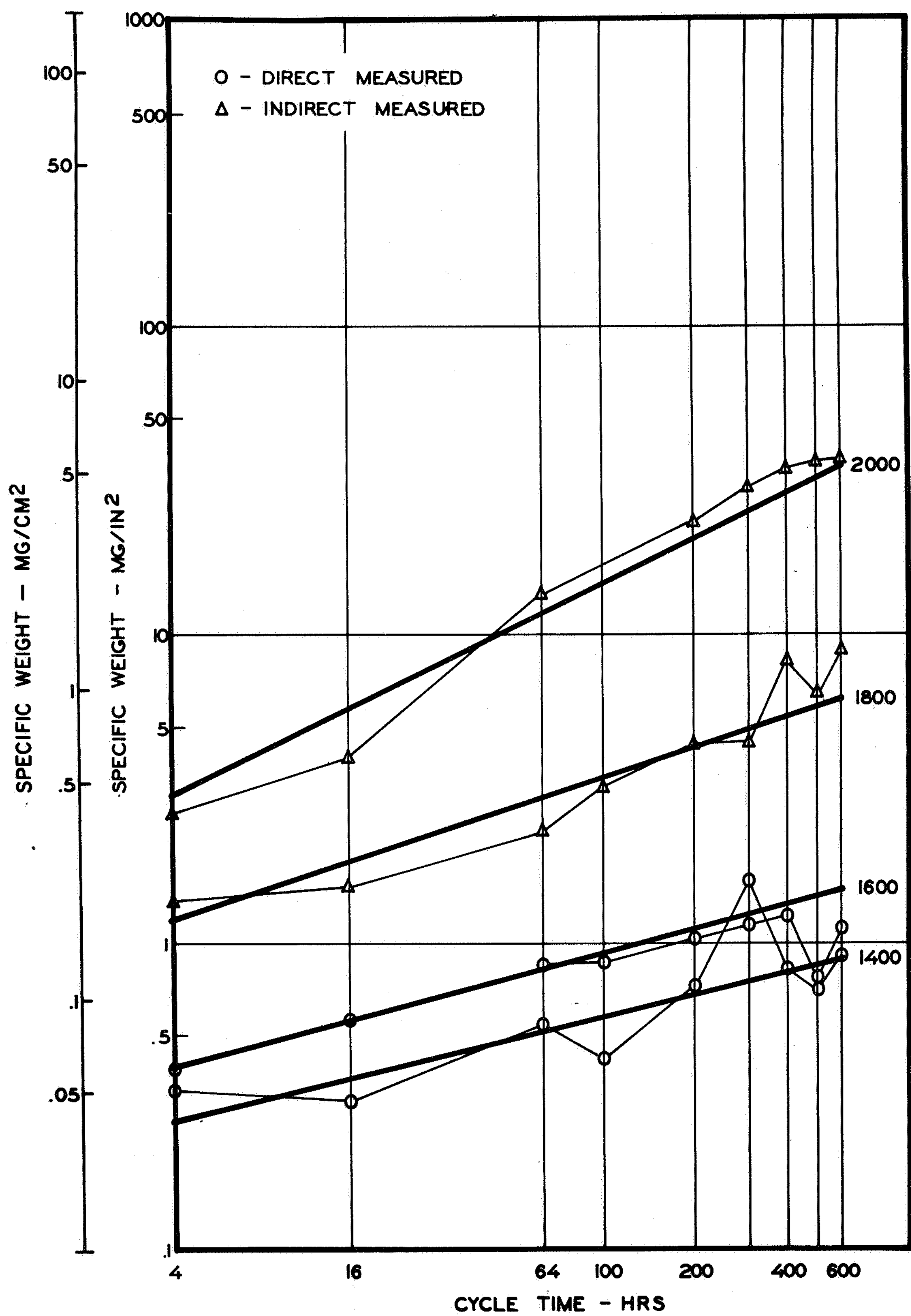


Figure A2-5 Specific total oxidation weight gain: Alloy 5, Chromel A.

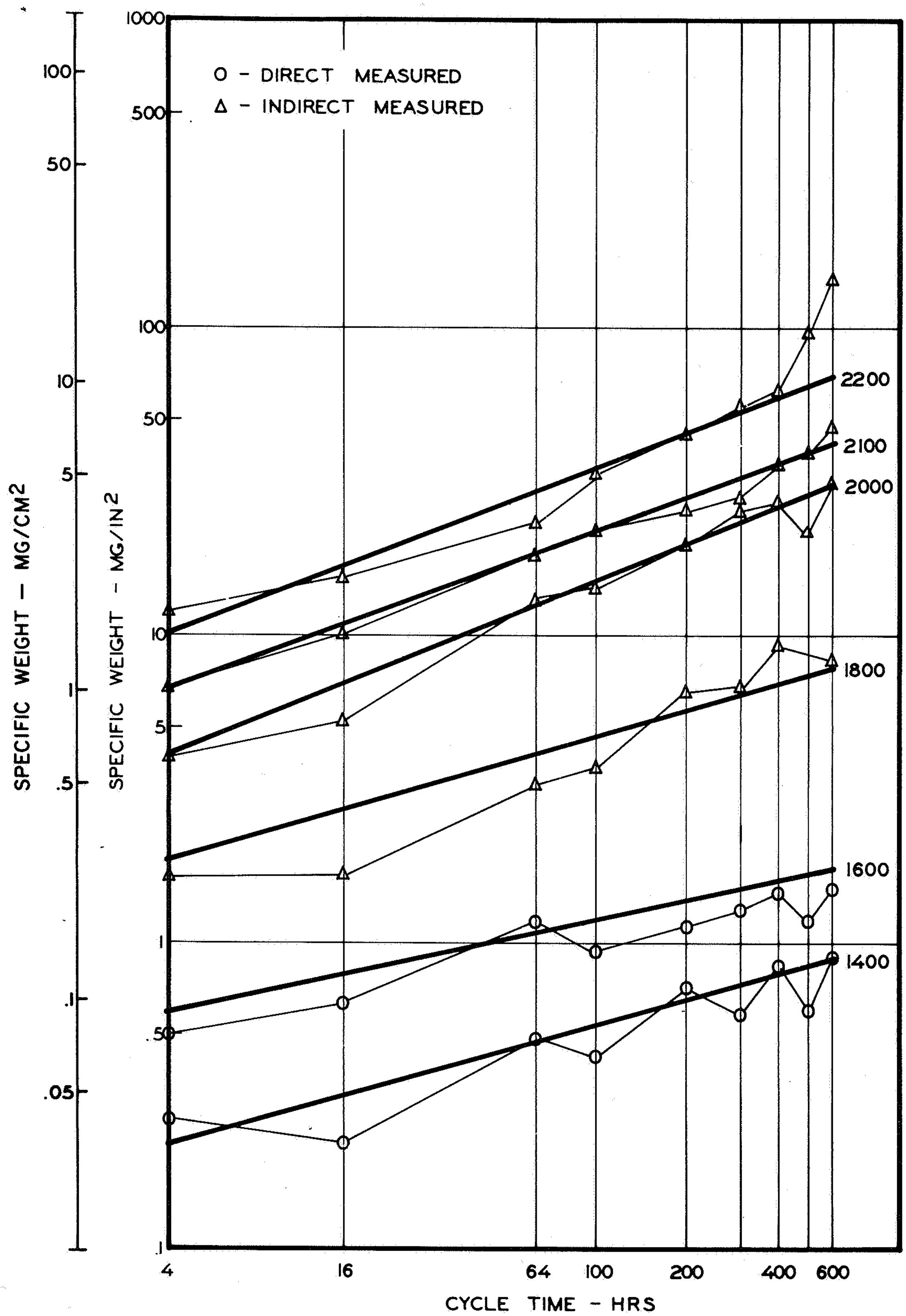


Figure A2-6 Specific total oxidation weight gain: Alloy 6, DH 242.

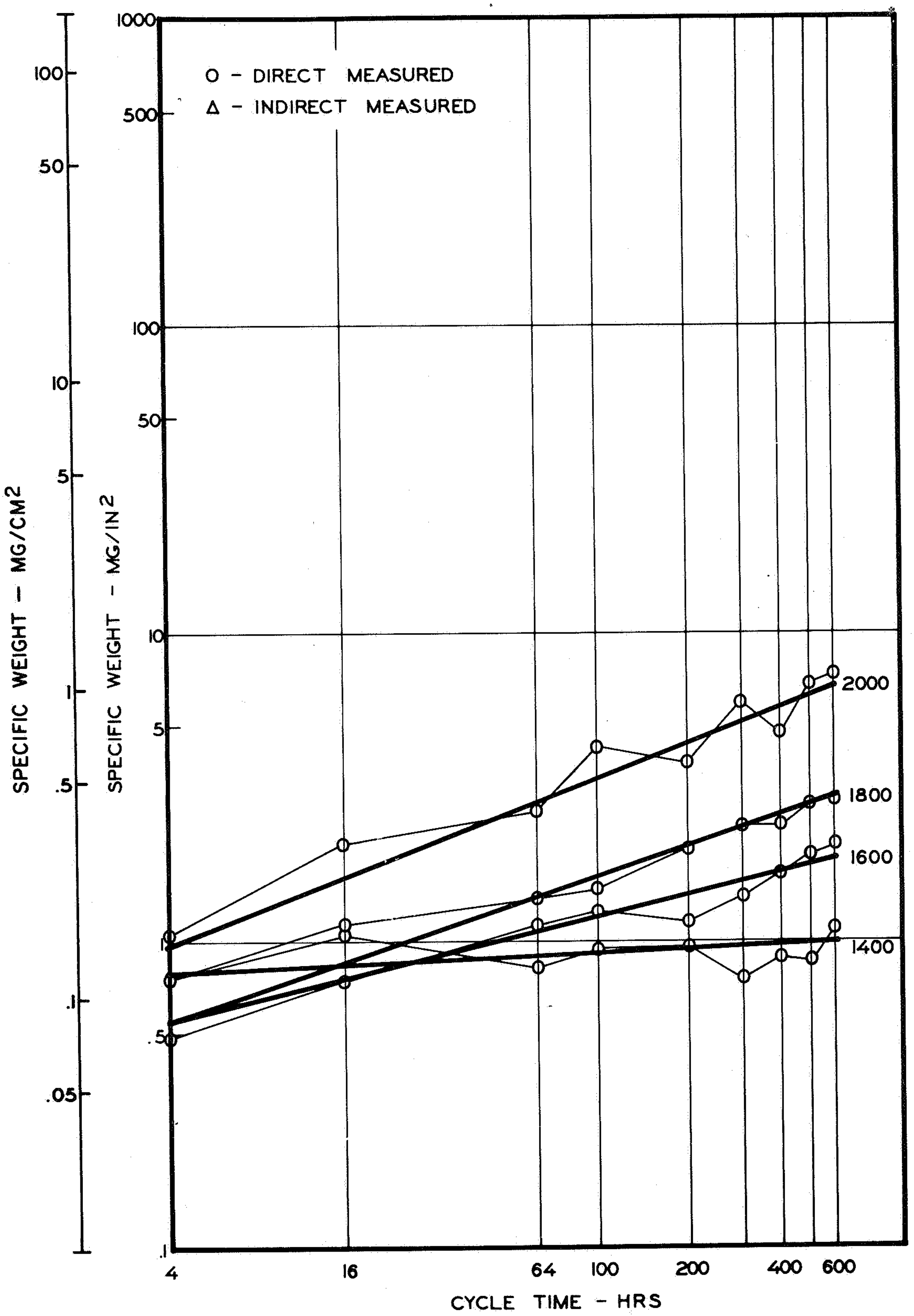


Figure A2-7 Specific total oxidation weight gain: Alloy 7, GE 1541.

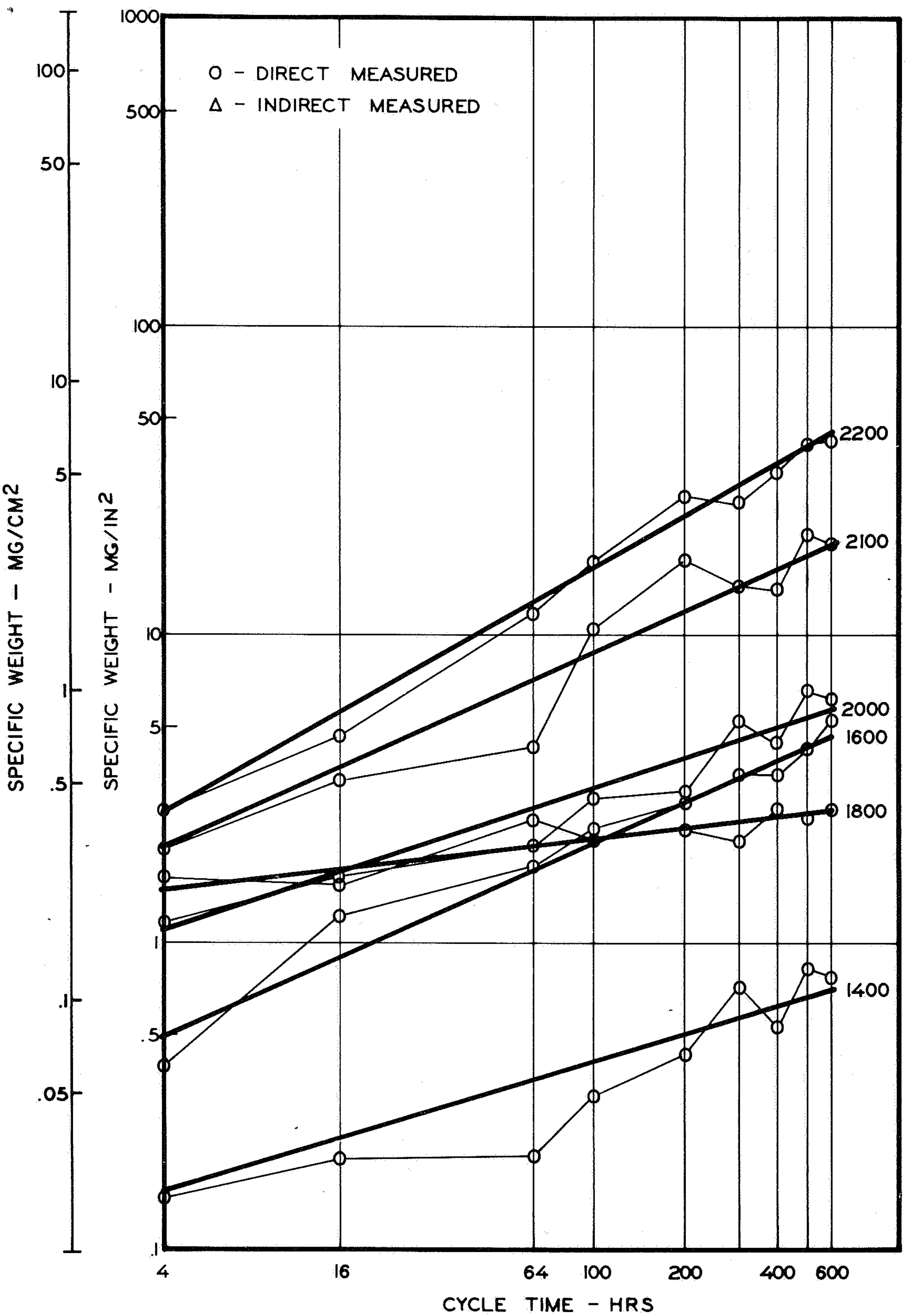


Figure A2-8 Specific total oxidation weight gain: Alloy 8, Hoskins 875.

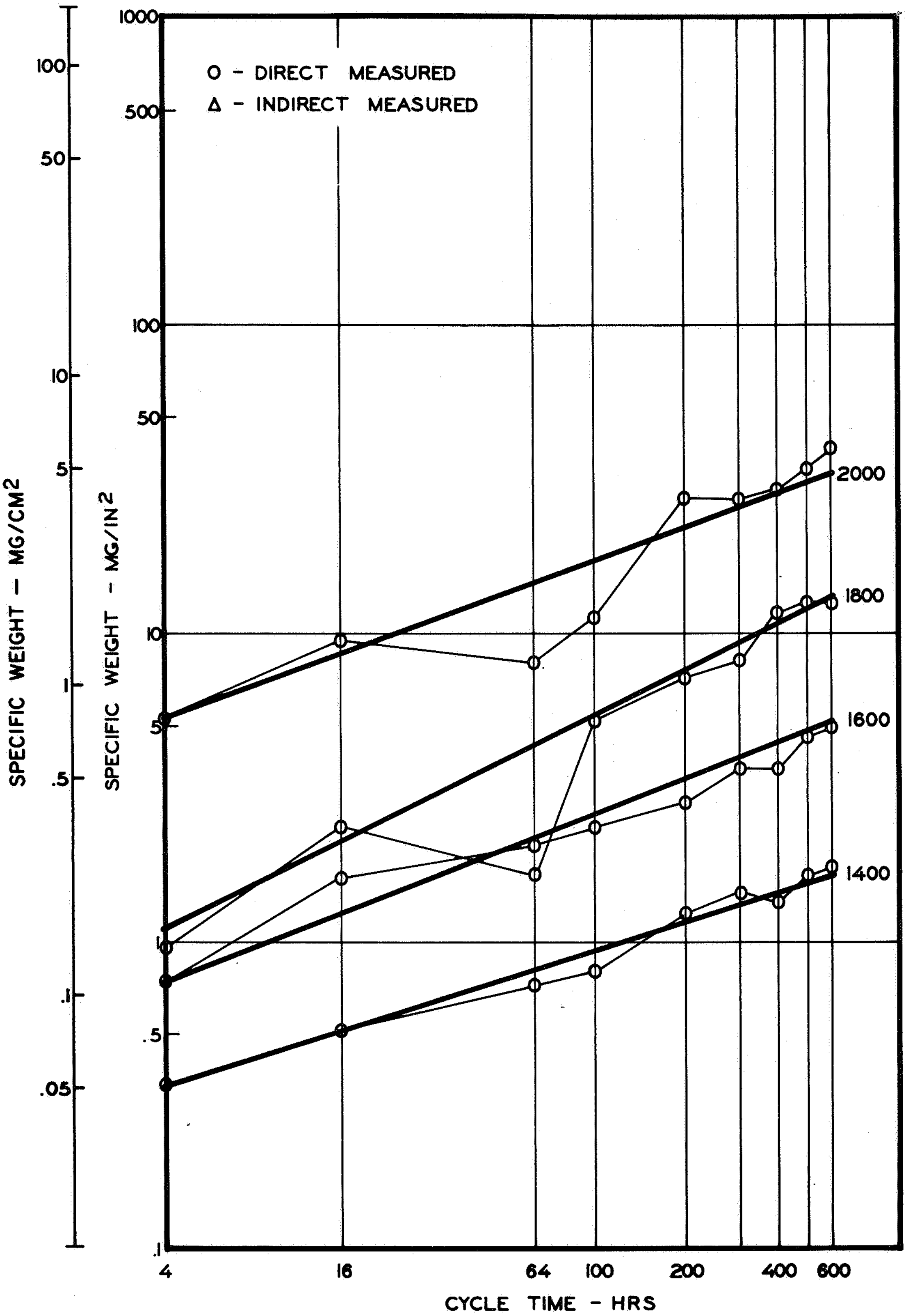


Figure A2-9 Specific total oxidation weight gain: Alloy 9, RA 333.

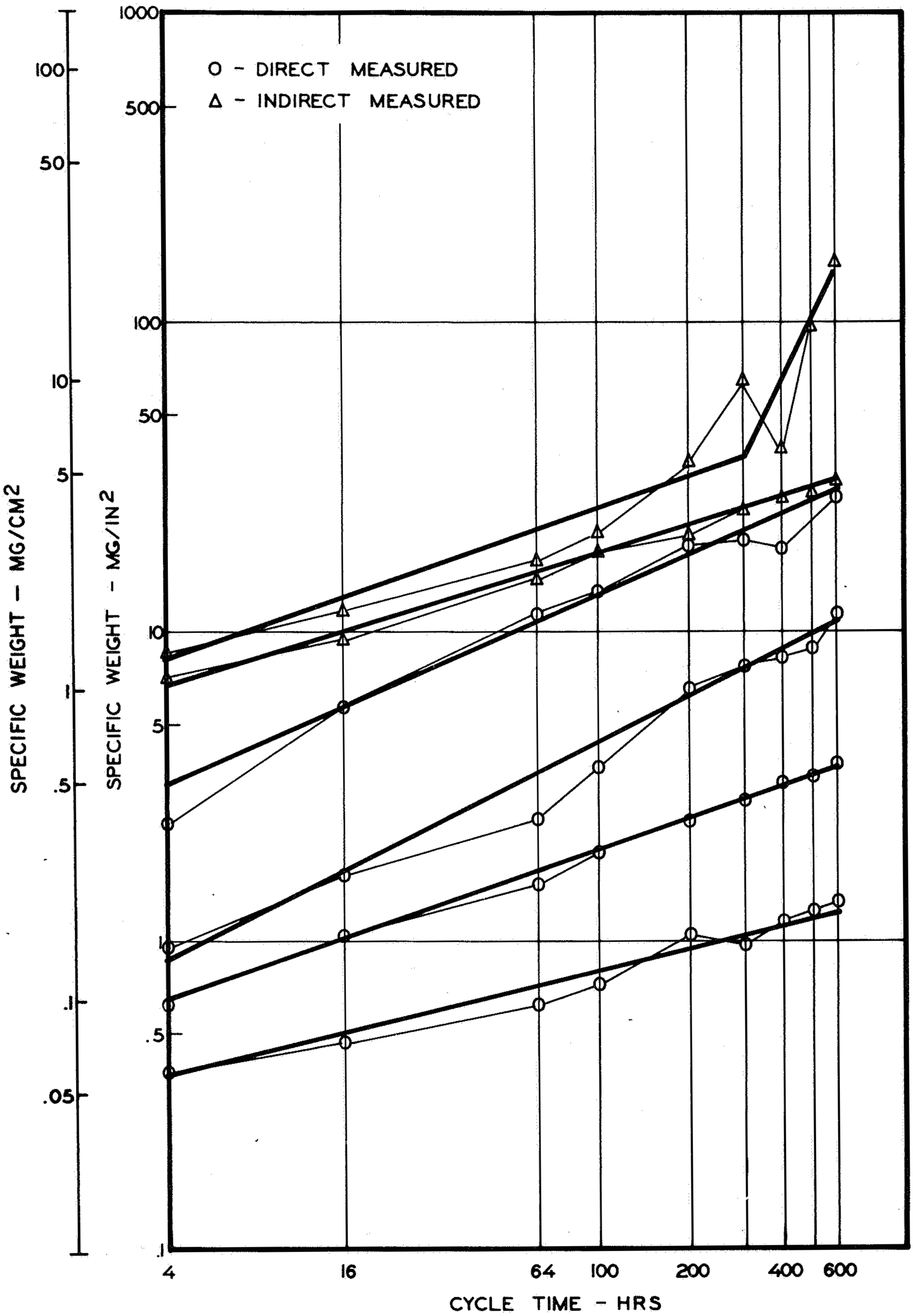


Figure A2-10 Specific total oxidation weight gain: Alloy 10, Hastelloy X.

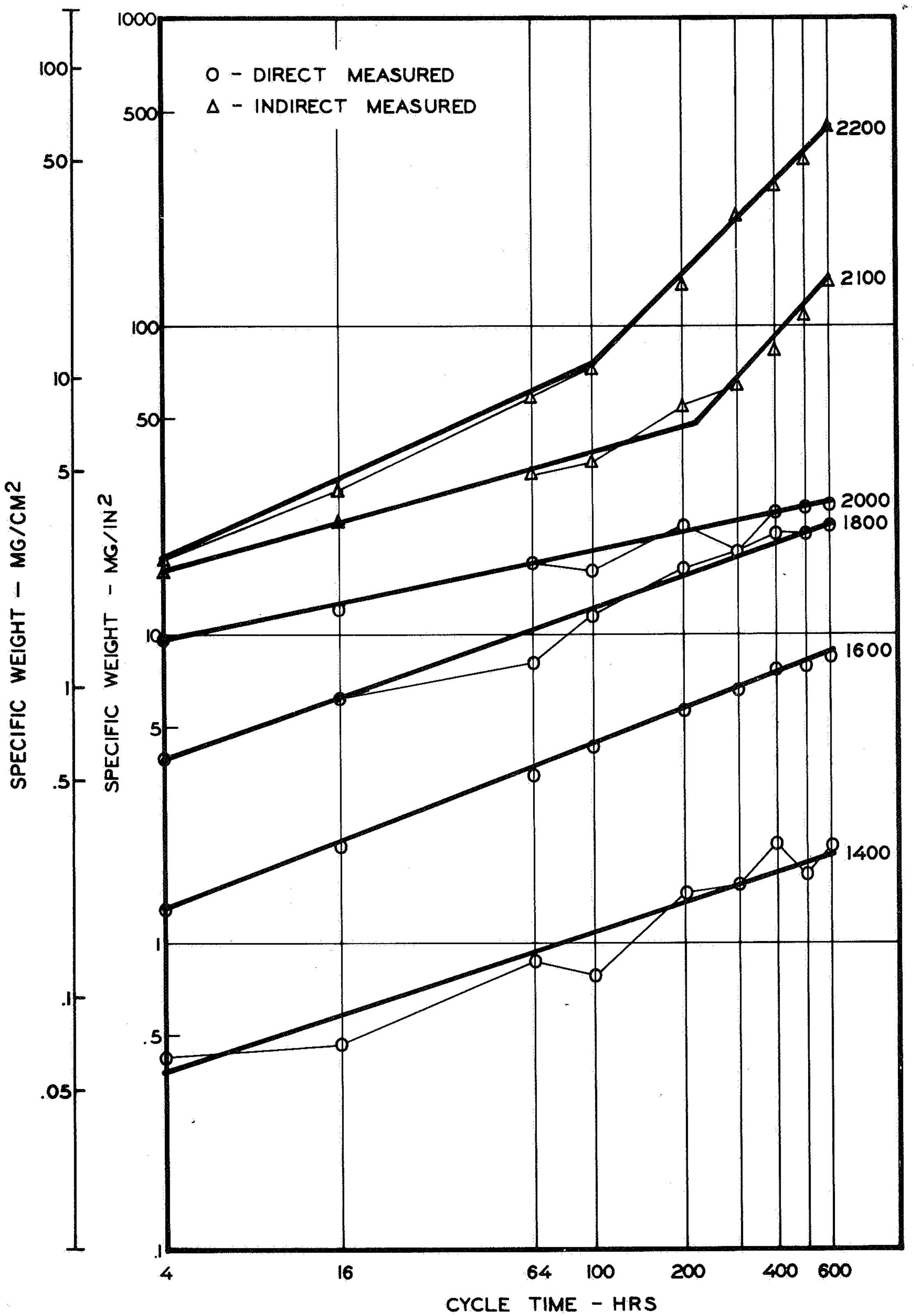


Figure A2-11 Specific total oxidation weight gain: Alloy 11, Udimet 500.

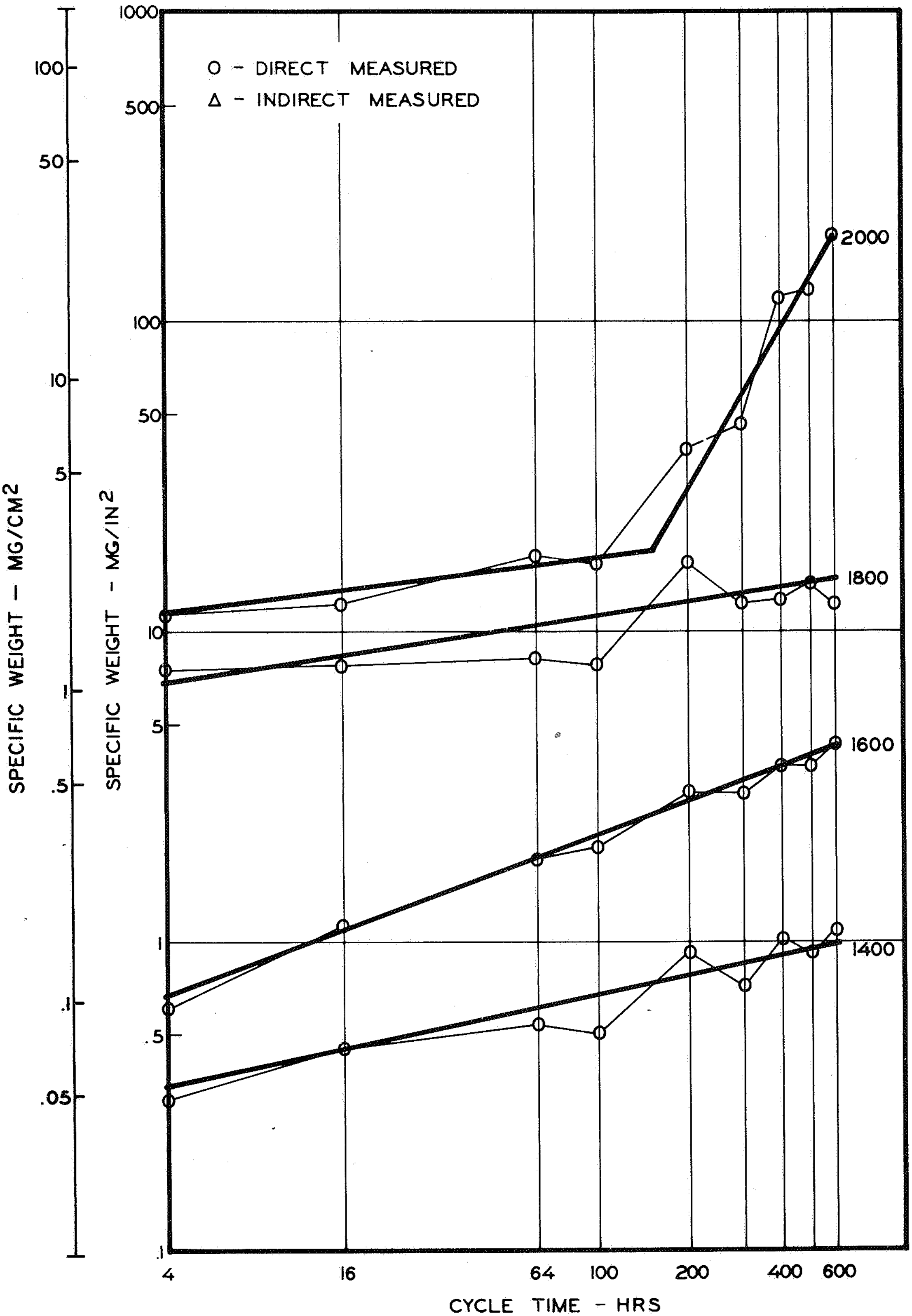


Figure A2-12 Specific total oxidation weight gain: Alloy 12, Haynes 25.

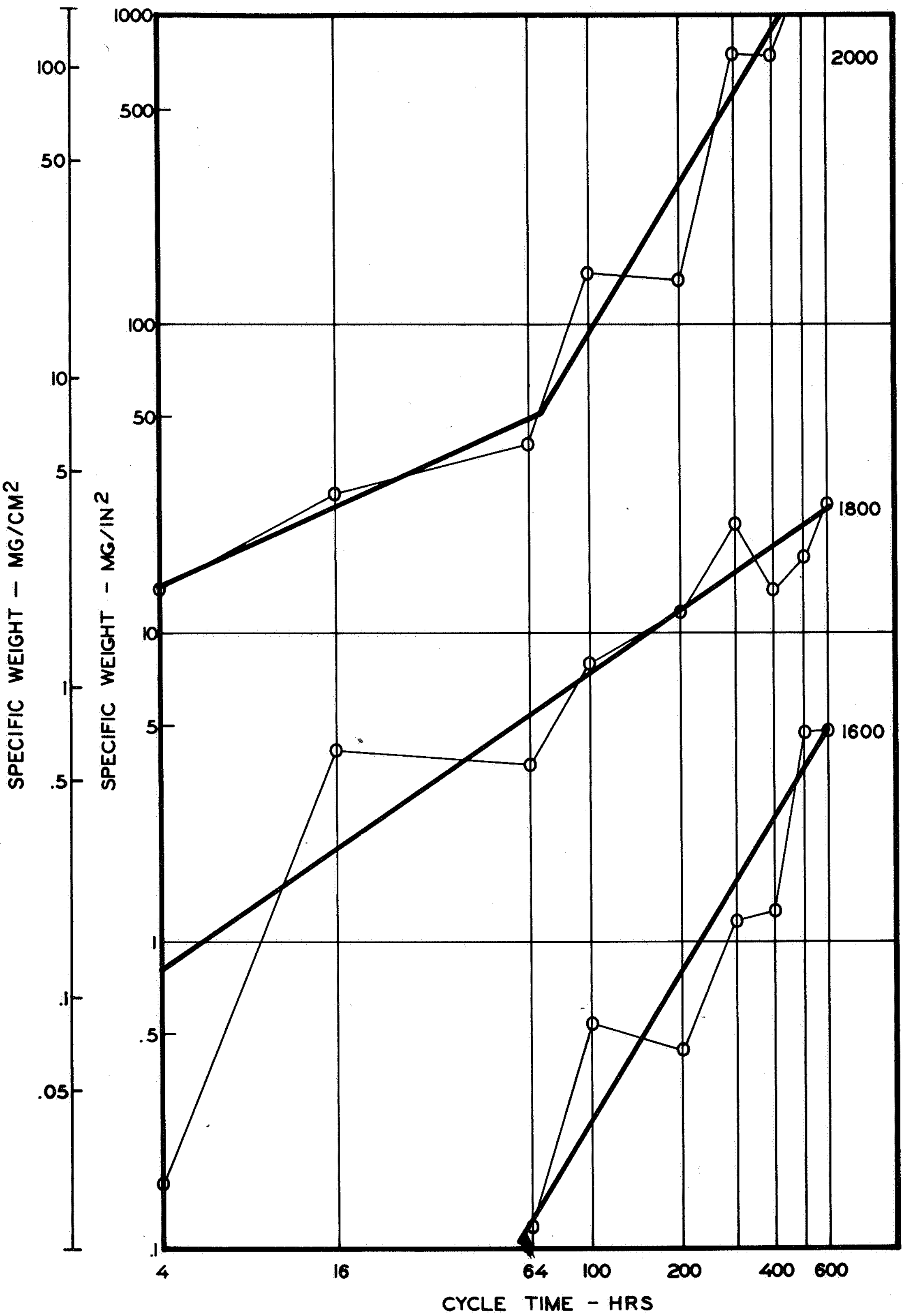


Figure A2-13 Specific oxide spall weight: Alloy 1, N 155.

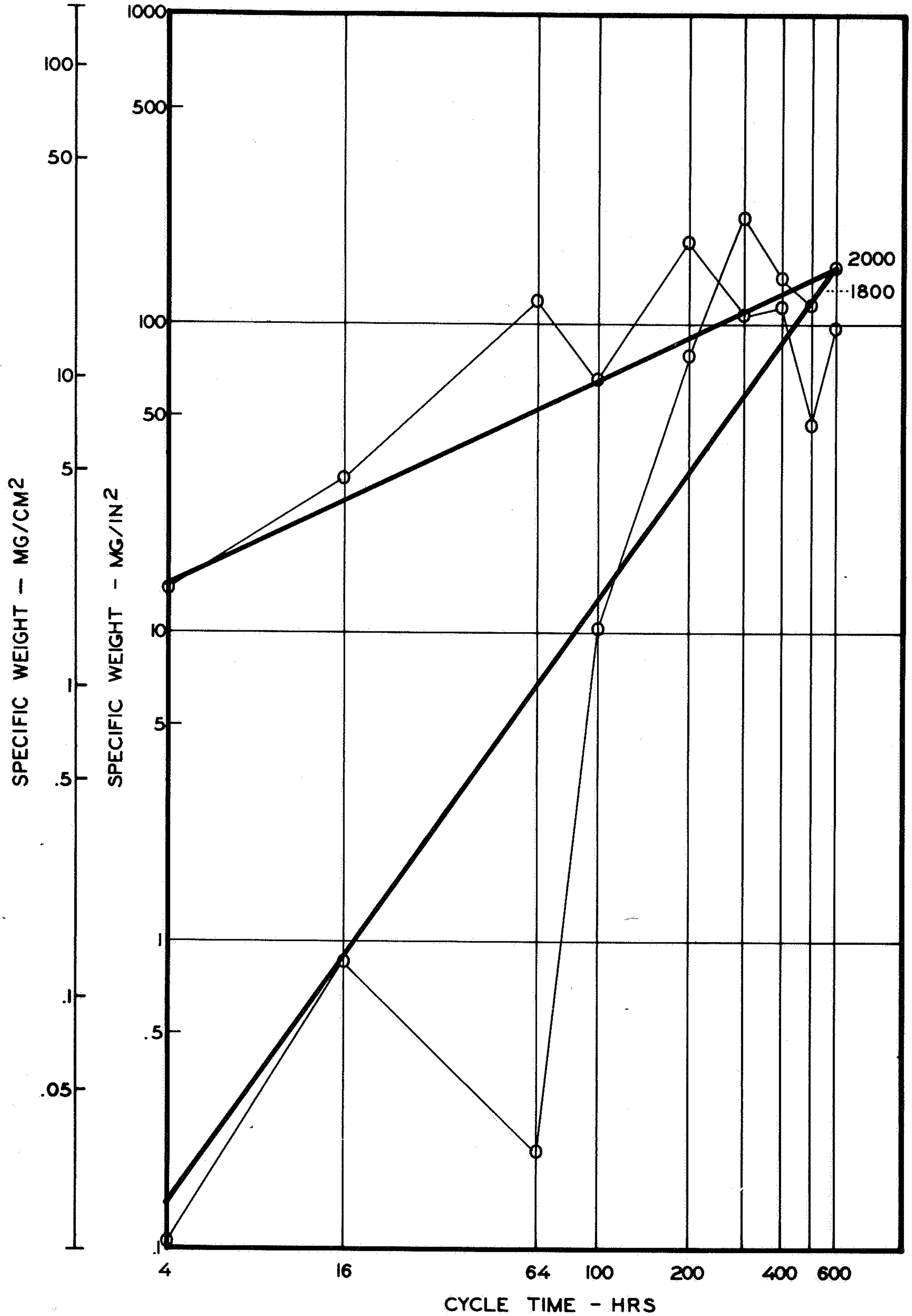


Figure A2-14 Specific oxide spall weight: Alloy 2, TD nickel.

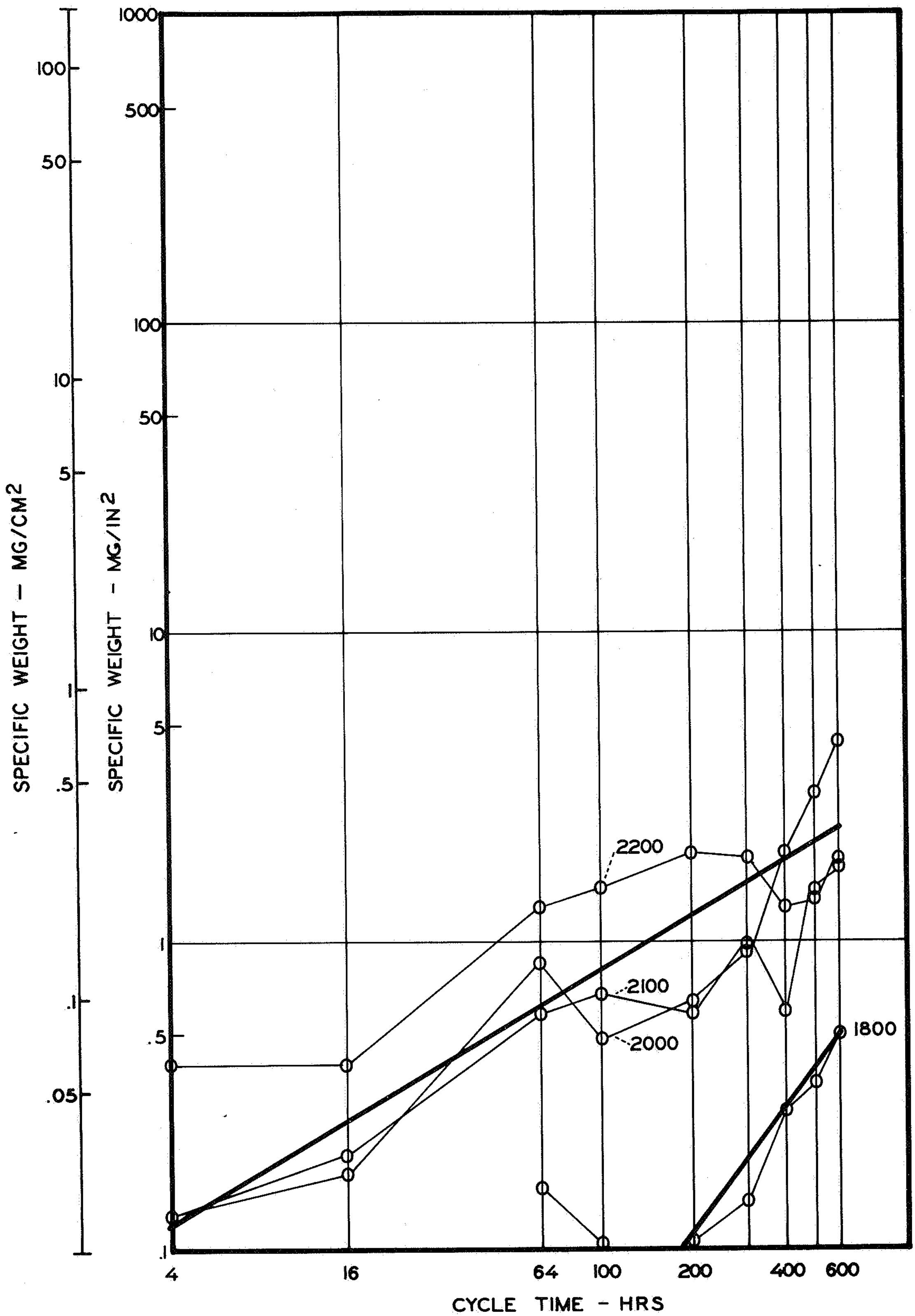


Figure A2-15 Specific oxide spall weight: Alloy 3, TD nickel-chromium.

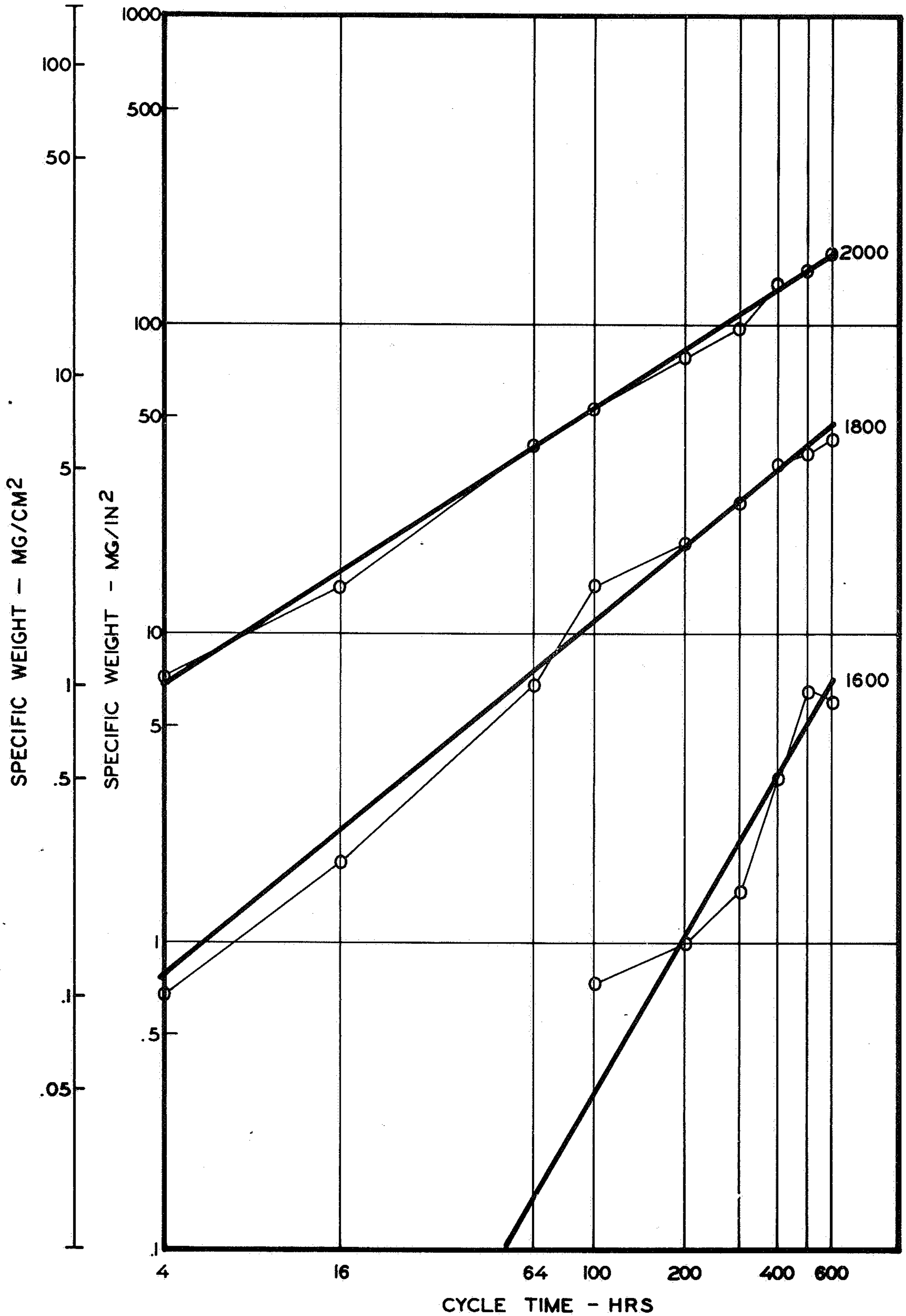


Figure A2-16 Specific oxide spall weight: Alloy 4, Bendel 65-35.

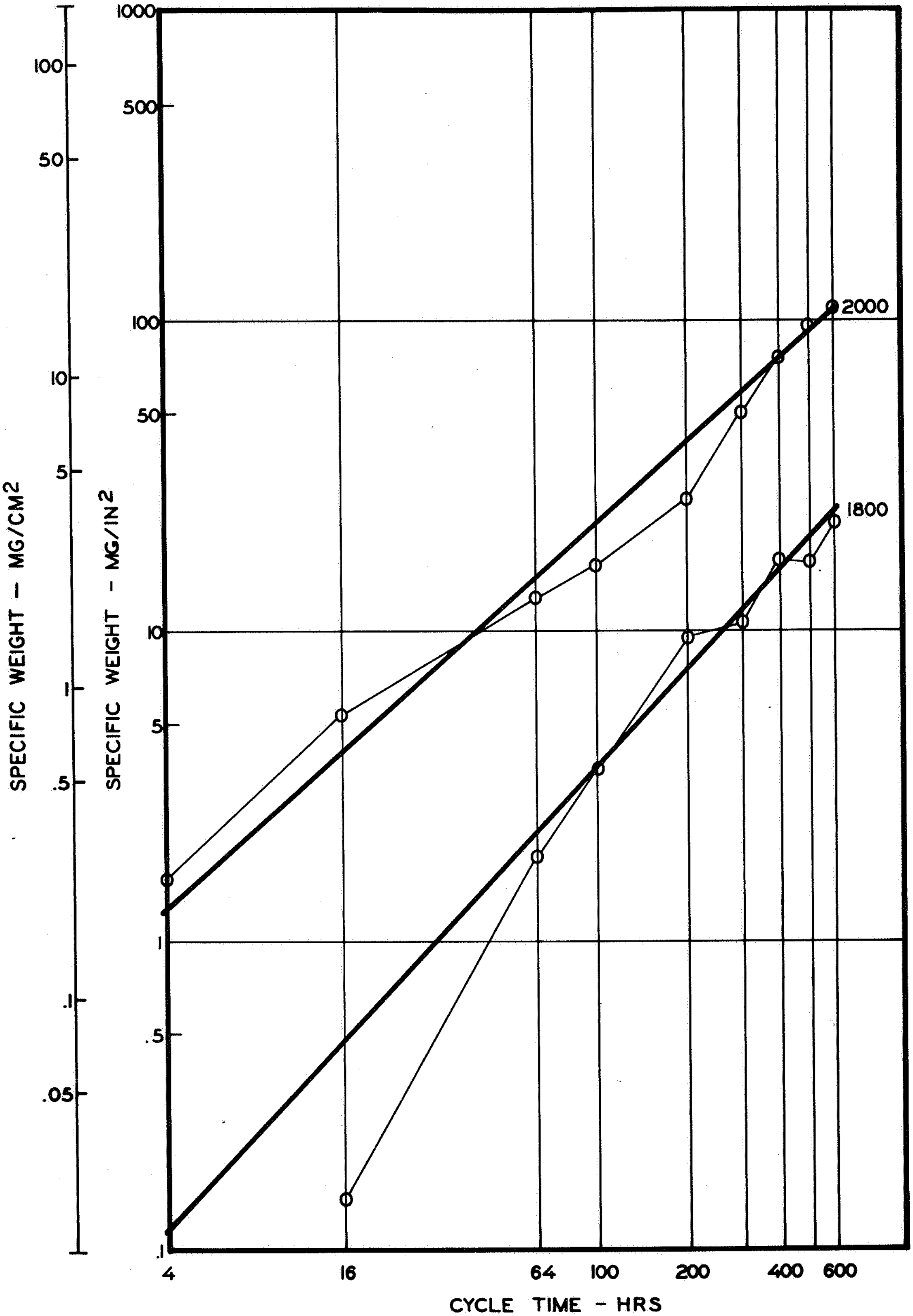


Figure A2-17 Specific oxide spall weight: Alloy 5, Chromel A.

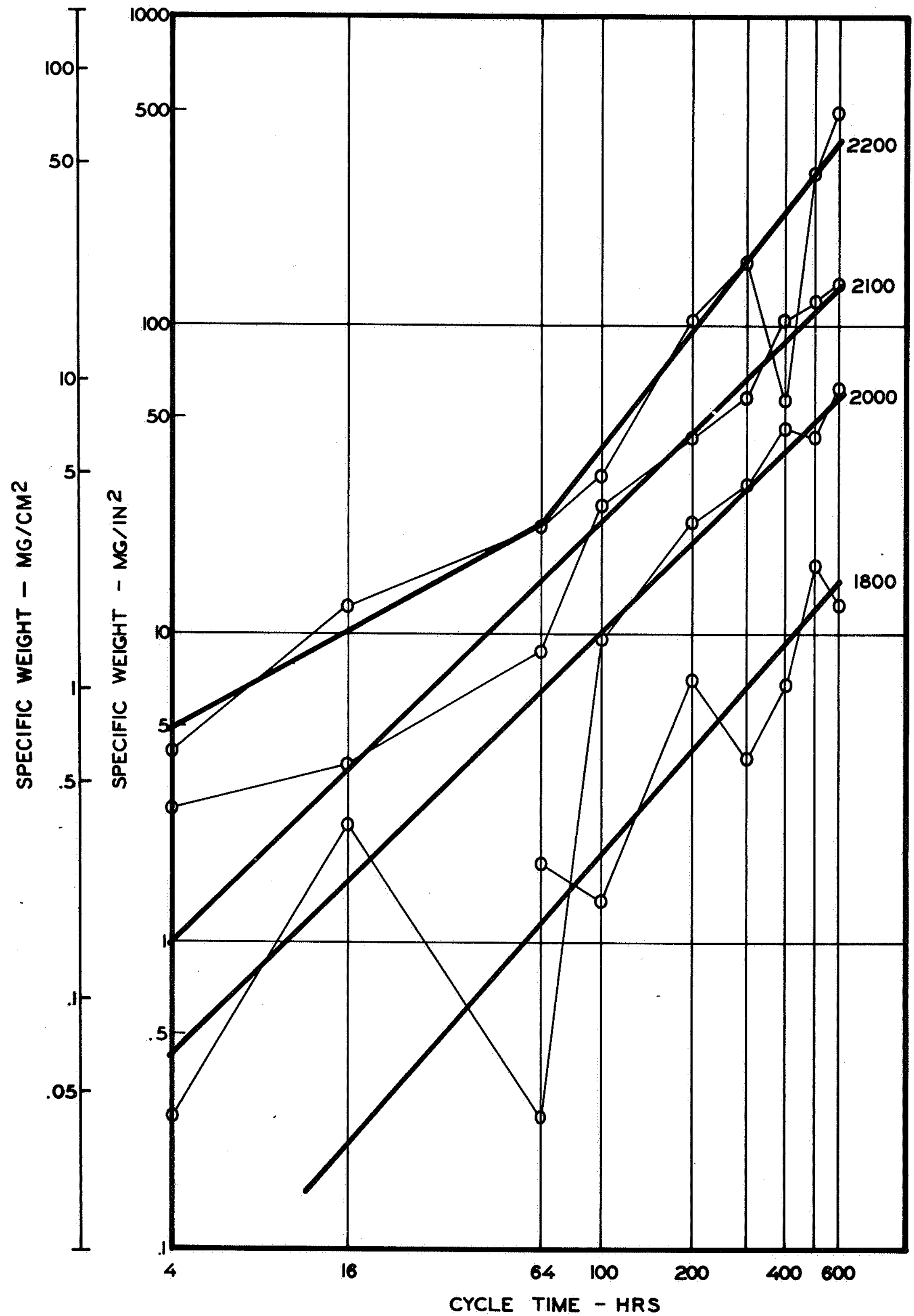


Figure A2-18 Specific oxide spall weight: Alloy 6, DH 242.

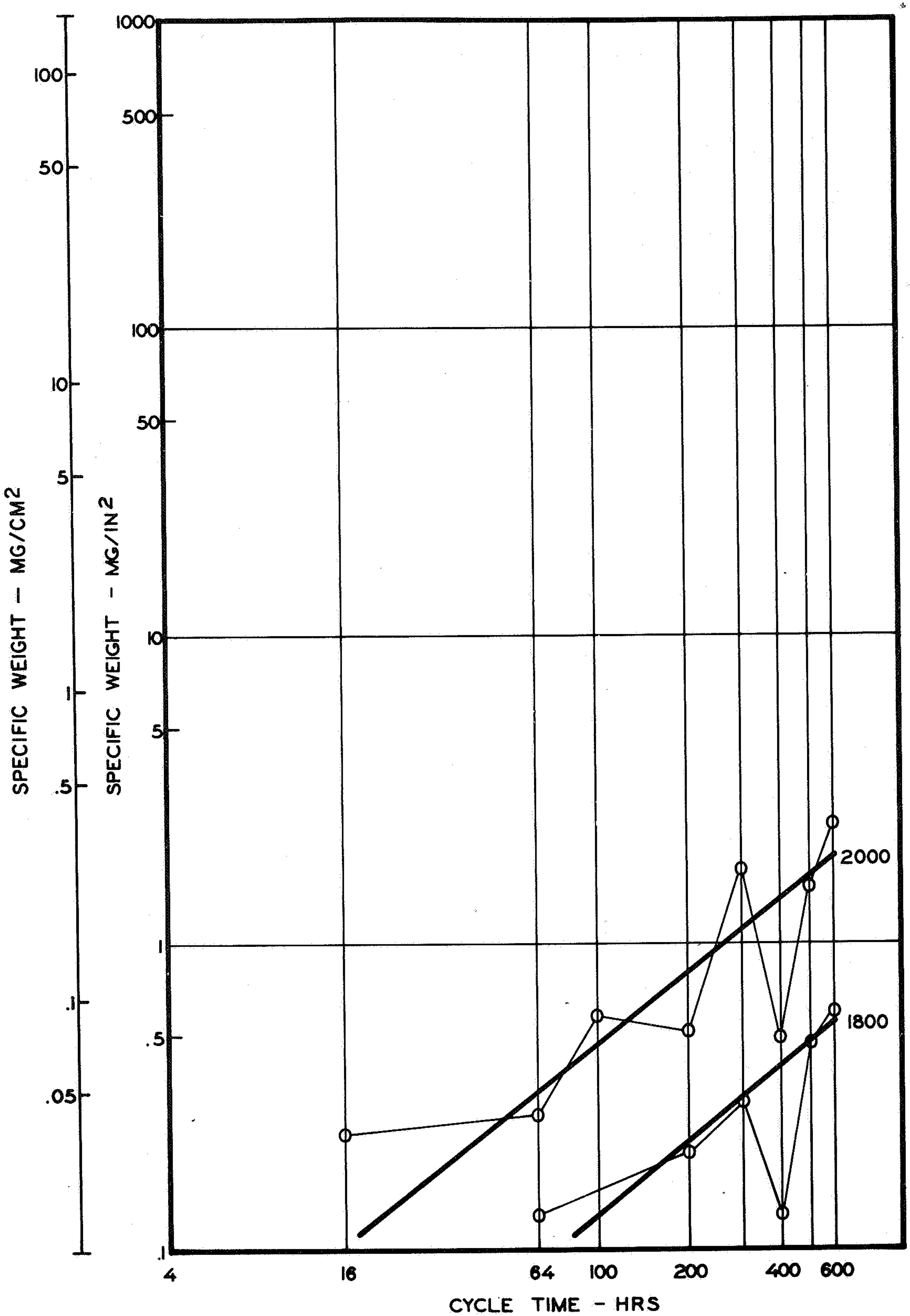


Figure A2-19 Specific oxide spall weight: Alloy 7, GE 1541.

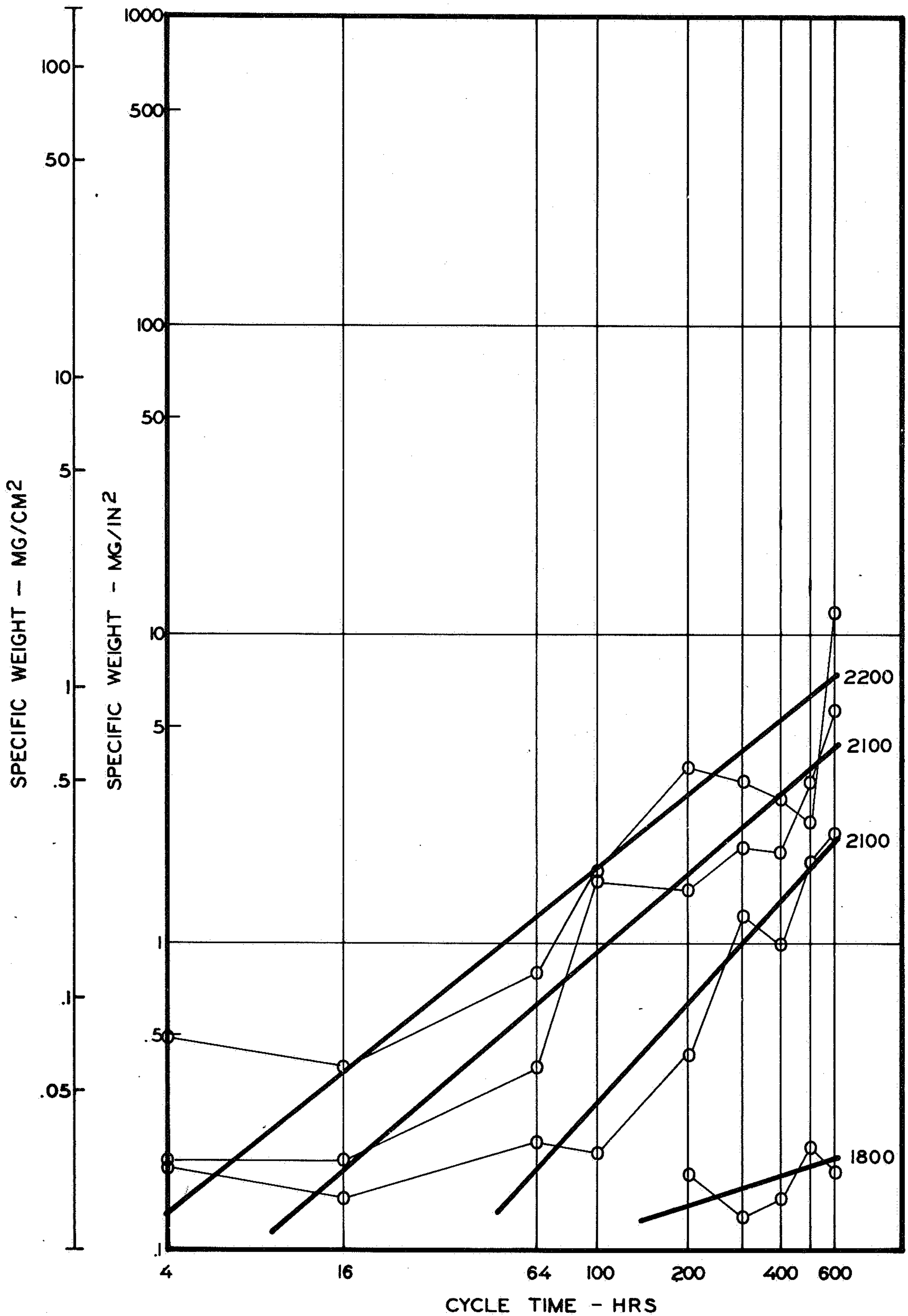


Figure A2-20 Specific oxide spall weight: Alloy 8, Hoskins 875.

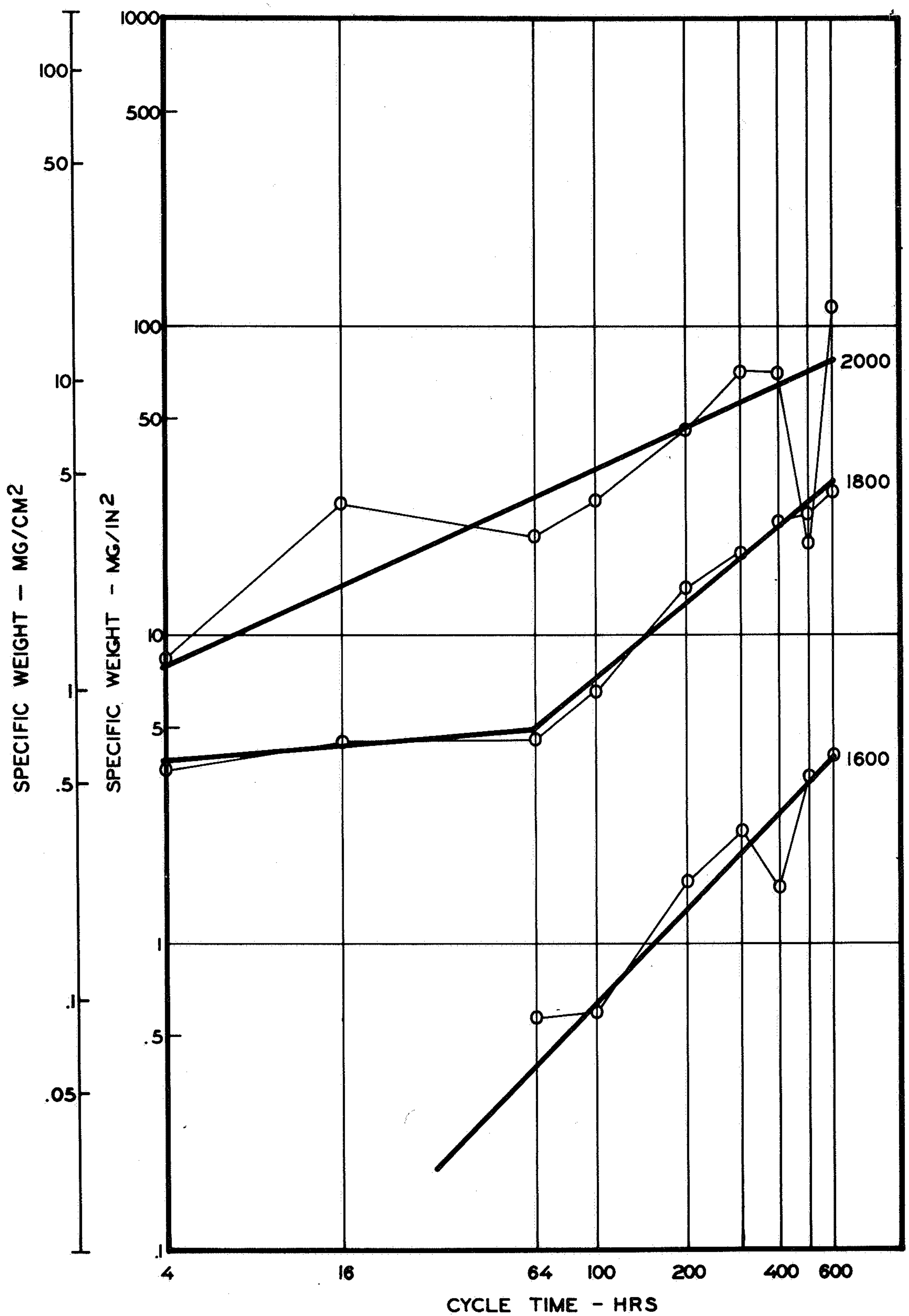


Figure A2-21 Specific oxide spall weight: Alloy 9, RA 333.

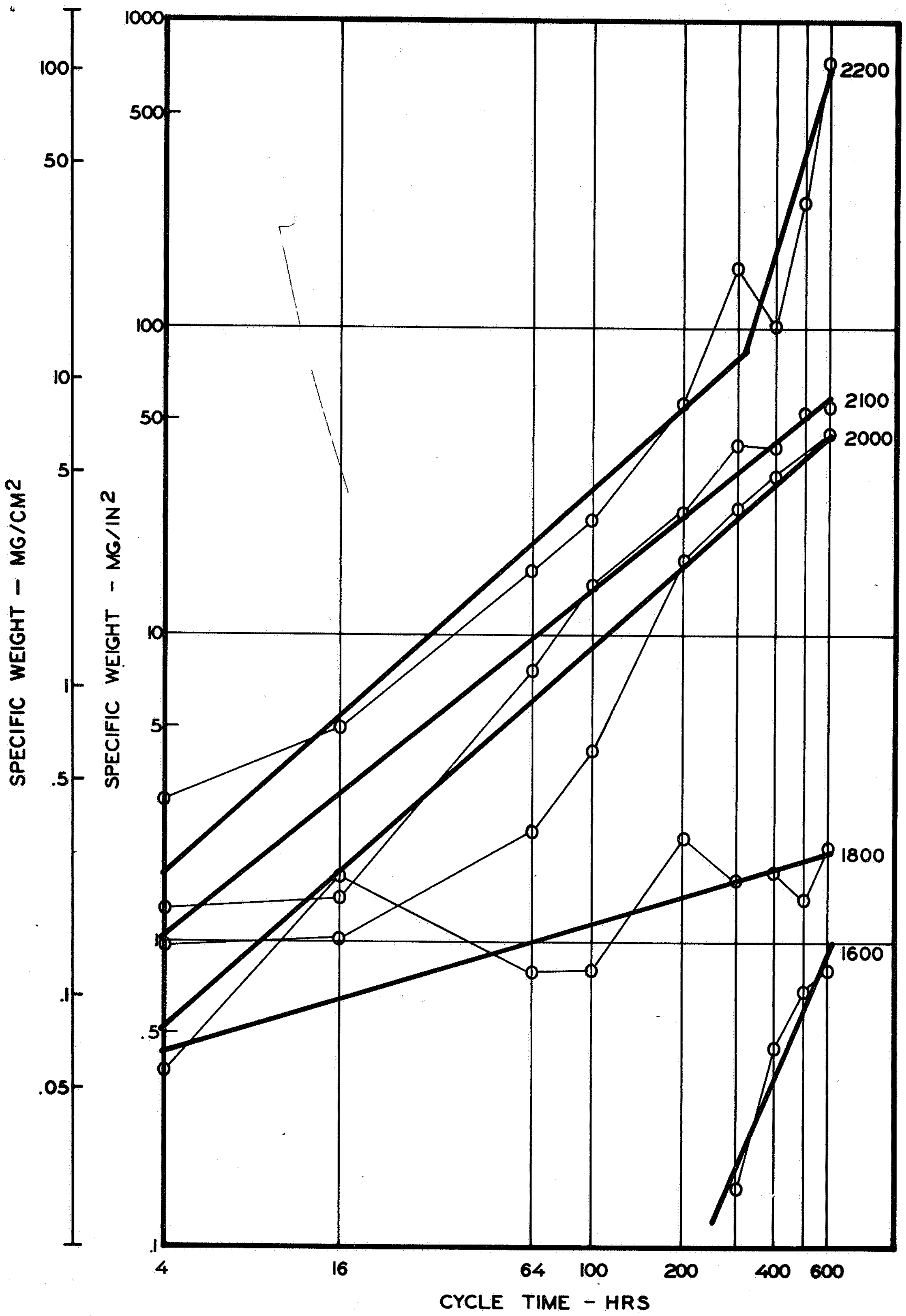


Figure A2-22 Specific oxide spall weight: Alloy 10, Hastelloy X.

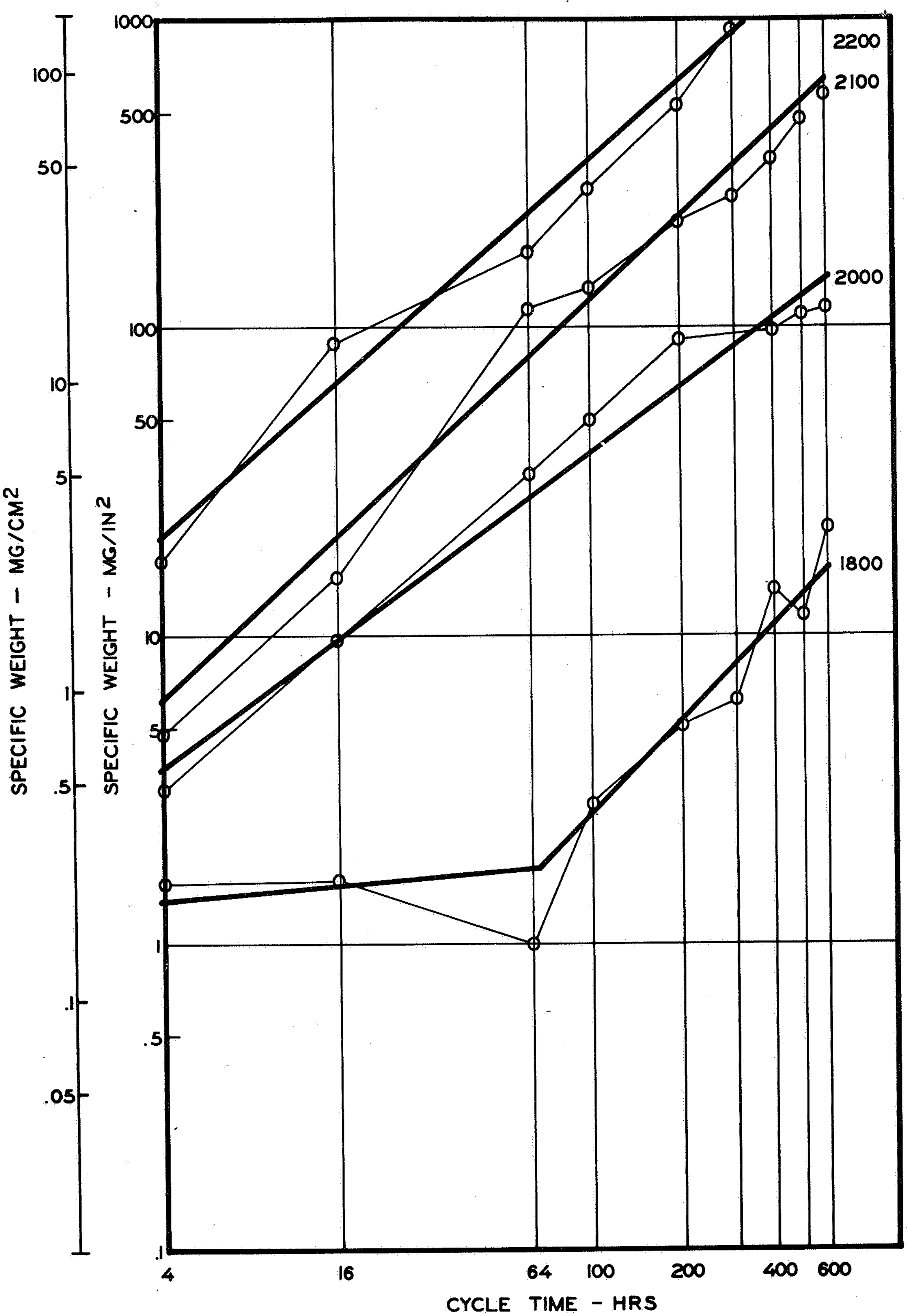


Figure A2-23 Specific oxide spall weight: Alloy 11, Udimet 500.

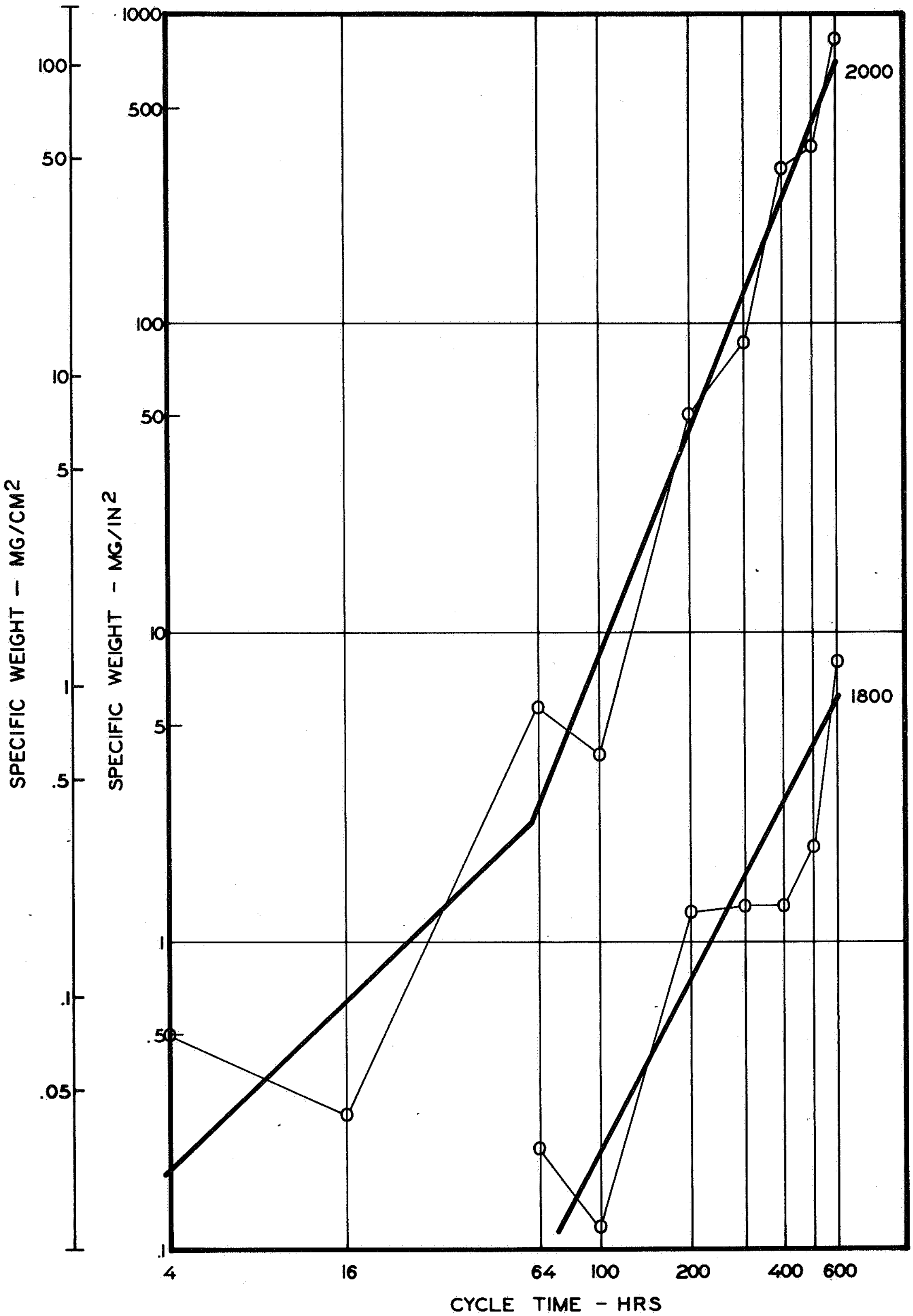


Figure A2-24 Specific oxide spall weight: Alloy 12, Haynes 25.

APPENDIX 3
METALLOGRAPHIC EXAMINATION

CONTENTS

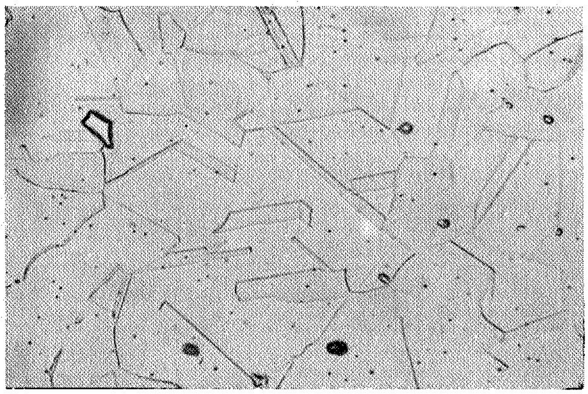
ALLOY	FIGURE	PAGE
1. N 155	A3-1	96
2. TD nickel	A3-2	98
3. TD nickel-chromium	A3-3	100
4. Bendel 65-35	A3-4	102
5. Chromel A	A3-5	104
6. DH 242	A3-6	106
7. GE 1541	A3-7	108
8. Hoskins 875	A3-8	110
9. RA 333	A3-9	112
10. Hastelloy X	A3-10	114
11. Udimet 500	A3-11	116
12. Haynes 25	A3-12	118

Selected photomicrographs* and photomacrographs for each alloy are reproduced with explanatory captions to demonstrate:

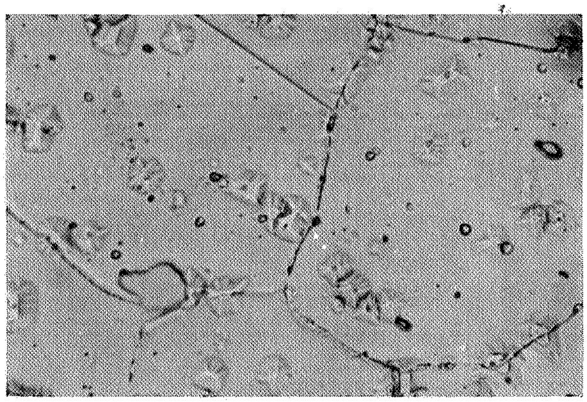
1. As-received microstructure
2. Sintered microstructure
3. Electron beam weld zone structure
4. Surface oxide appearance**
5. Oxide thickness and penetration
6. Oxidized microstructure

*All photographs are reproduced at the magnifications indicated.

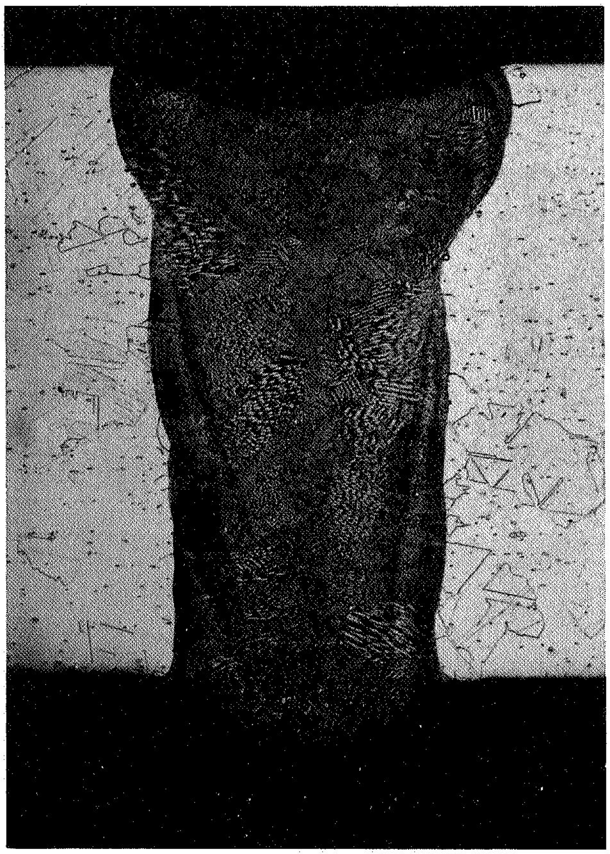
**Photographs of surface oxides are shown for 1800°F exposure only (except 2200°F for Alloy 3). Surface appearance at other temperatures is described in the captions, but not shown.



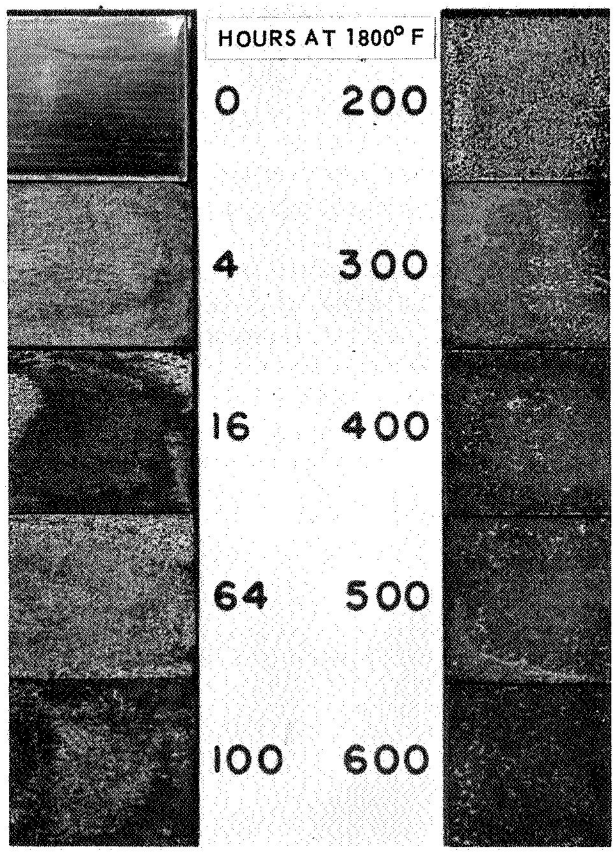
(1) As received: gamma solid solution with a few small intergranular carbides. 500X



(2) Sintered: grain growth with enlarged intergranular metal carbides. 500X



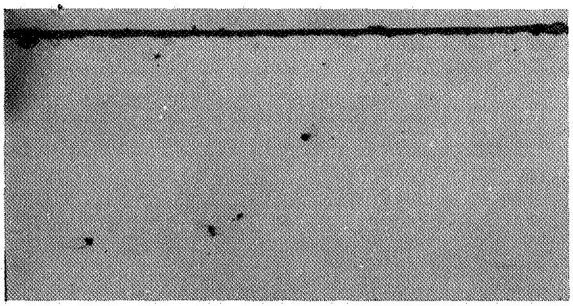
(3) Electron beam weld: sound, no voids, very fine-grained cast structure. 50X



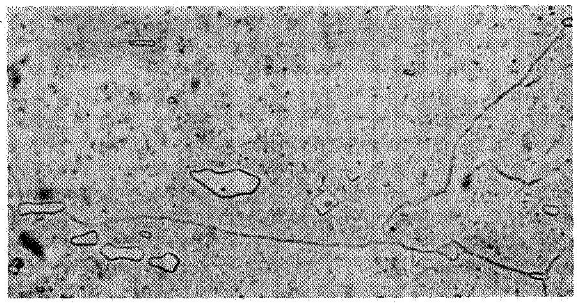
(4) Surface oxides: 1400°F, superficial oxides; 1600°F, roughened after 100 hours; 1800°F, some spall; 2000°F, considerable attack. 1.5X

Figure A3-1 Alloy 1, N155

1400°F

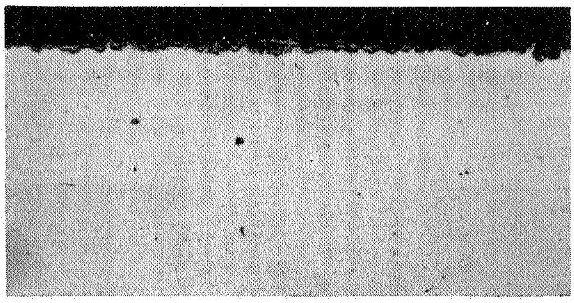


0.0001 inch adherent

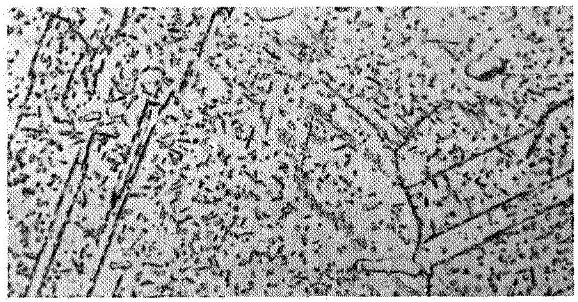


fine precipitate plus residual carbides

1600°F

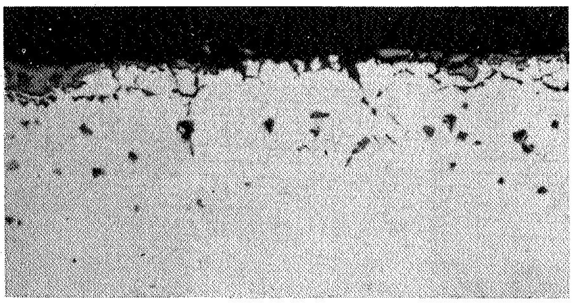


0.0002 inch adherent

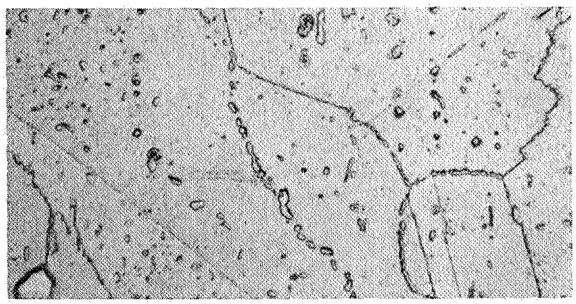


heavier precipitate, twinning

1800°F

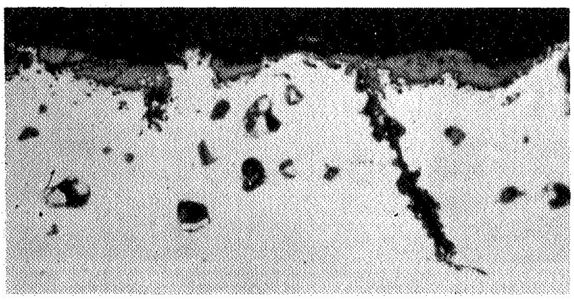


0.0025 inch penetration and spalling

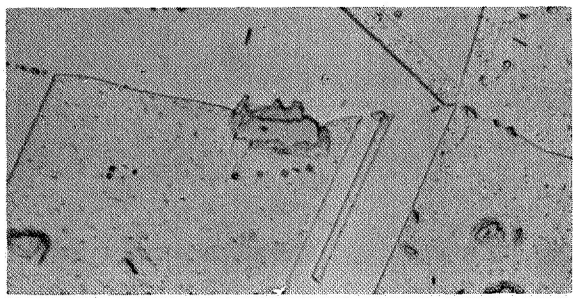


grain boundary carbides, fine precipitate

2000°F



0.005 inch spalling

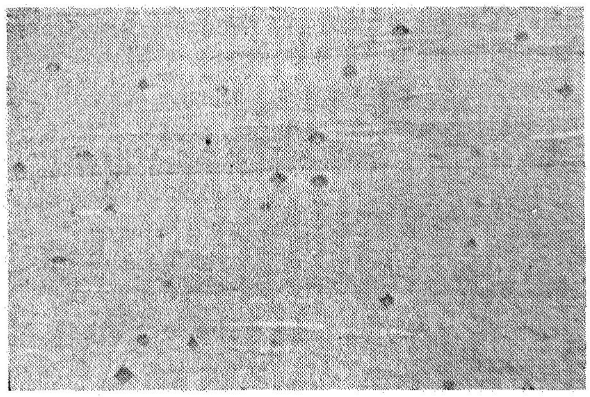


a few large carbides, some fine precipitate

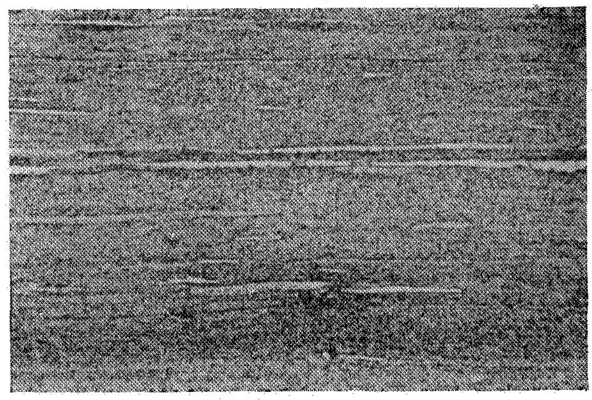
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

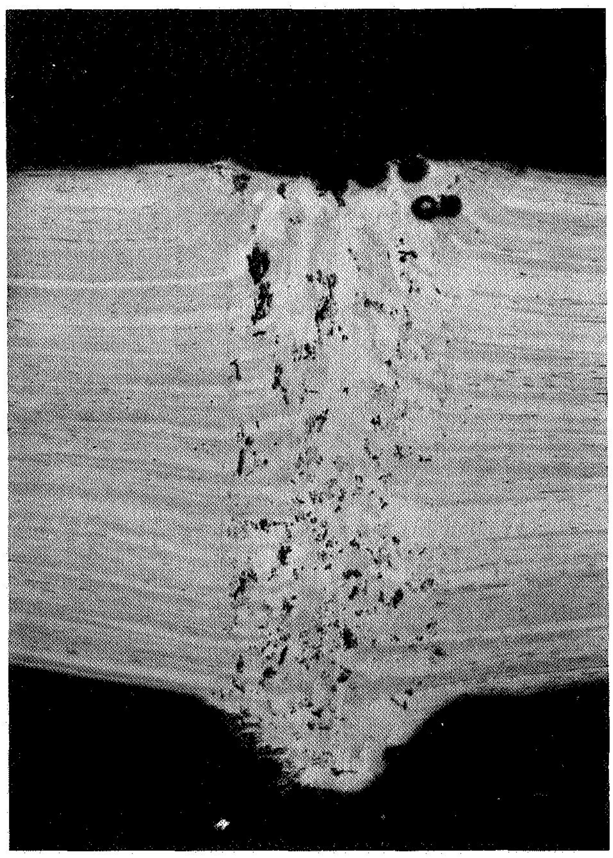
Figure A3-1 Alloy 1, N155



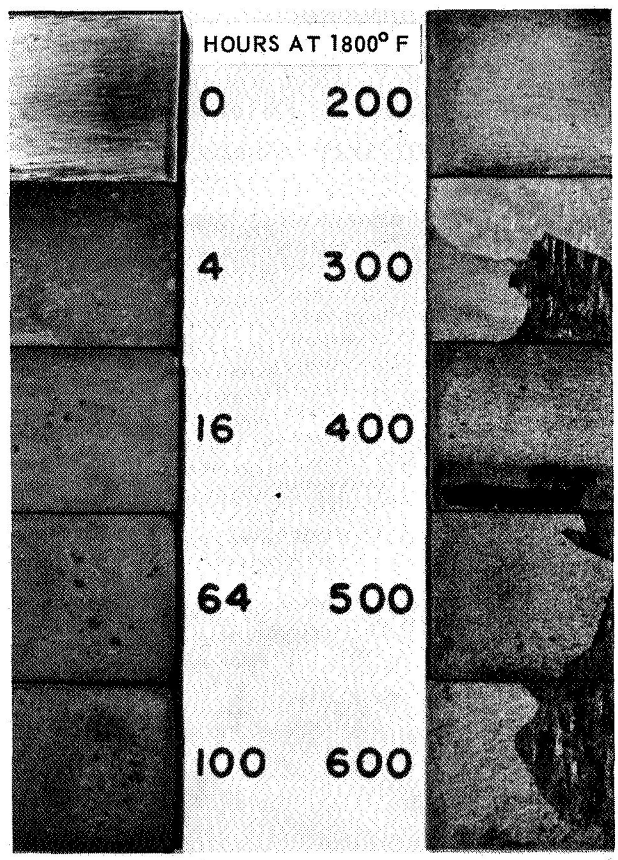
(1) As received: fine unresolved dispersion with random agglomerates and unimpregnated elongated grains. 500X



(2) Sintered: little change, fewer agglomerates visible, probably due to chance. 500X

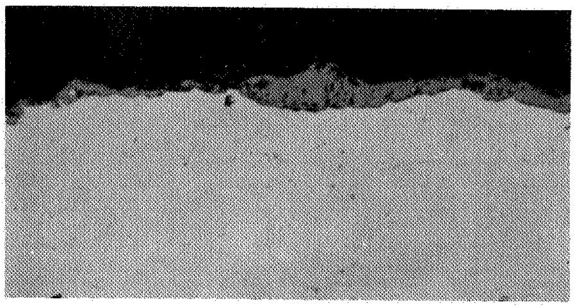


(3) Electron beam weld: partial agglomeration of dispersion. 50X



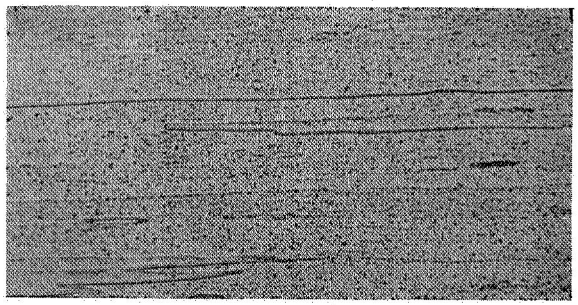
(4) Surface oxides: 1400°F, 1600°F, adherent, protective; 1800°F, considerable spall after 200 hours; 2000°F, spall after four hours. 1.5X

Figure A3-2 Alloy TD Nickel

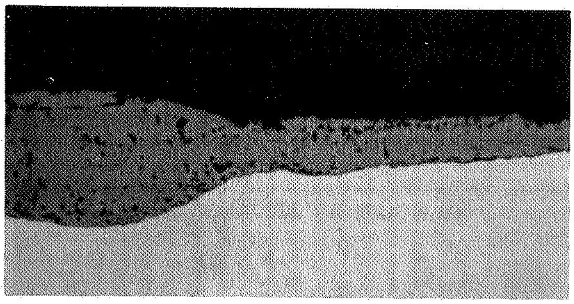


0.0003 inch

1400°F

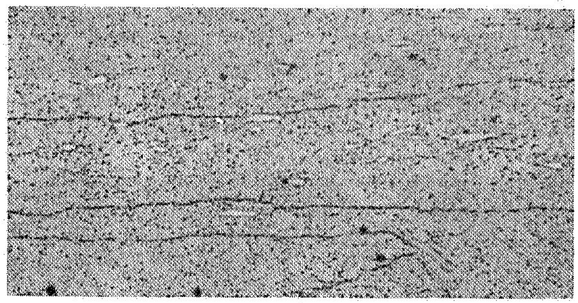


no change

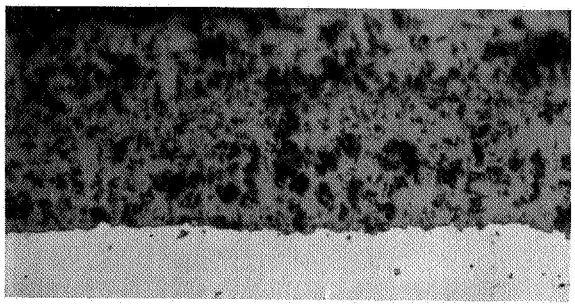


0.0011 inch, note varying thickness

1600°F

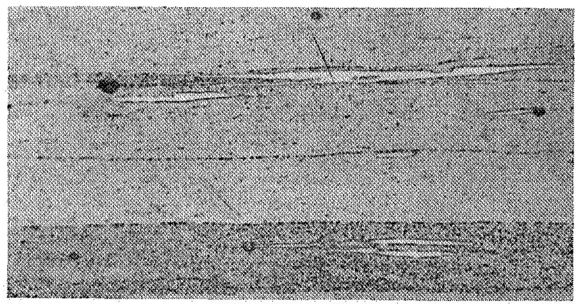


no change

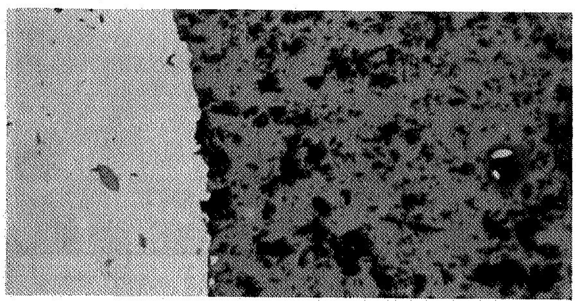


0.0045 inch, adherent only at a corner

1800°F

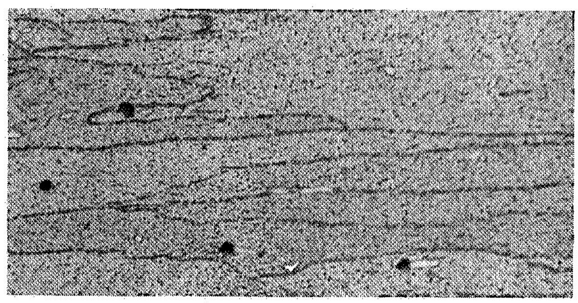


no change



0.011 inch, adherent only at a corner

2000°F

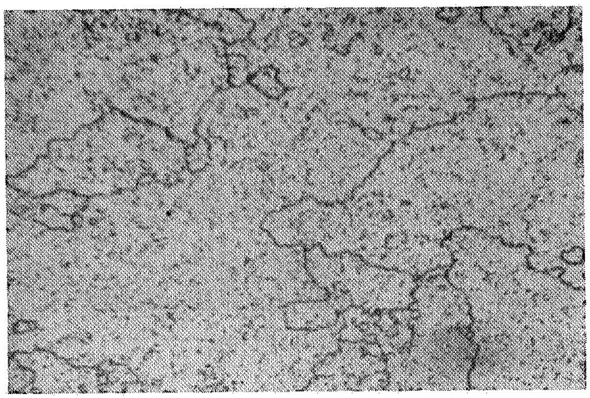


some apparent grain coarsening and agglomeration

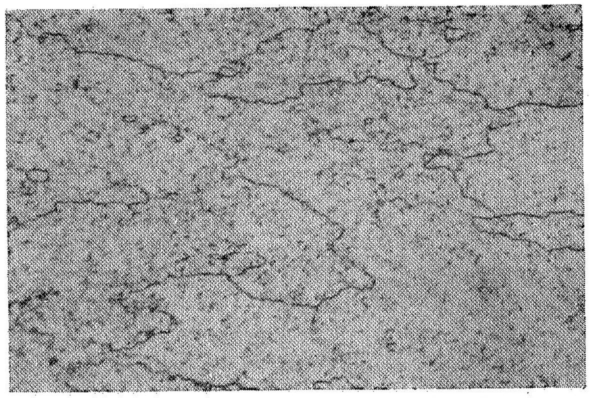
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

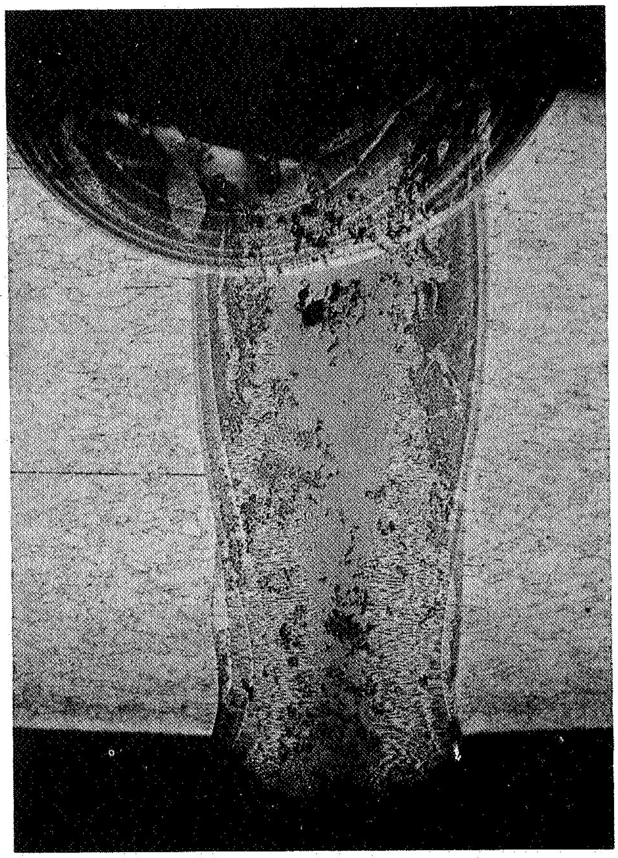
Figure A3-2 Alloy TD Nickel



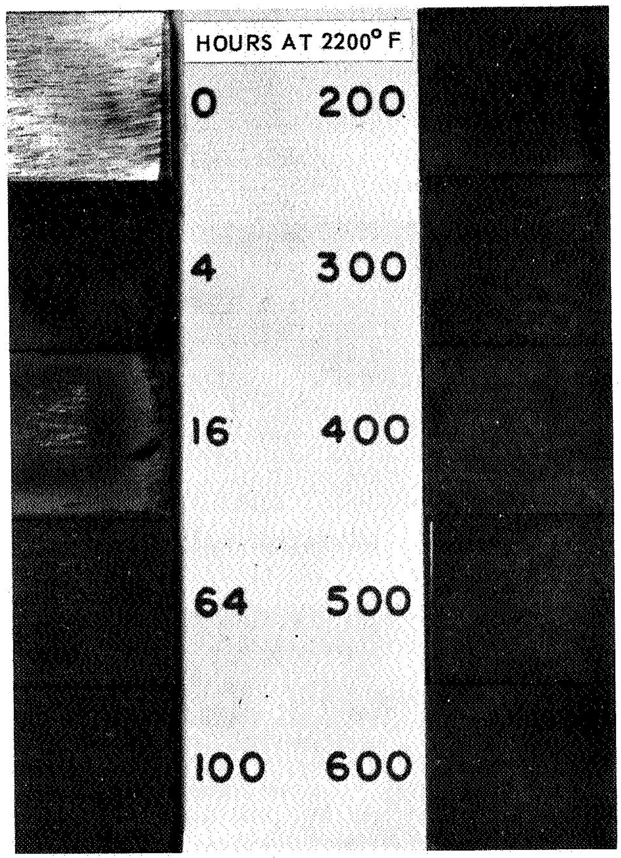
(1) As-received: fine resolved precipitate with probability of added unresolved precipitate. 500X



(2) Sintered: little change. 500X

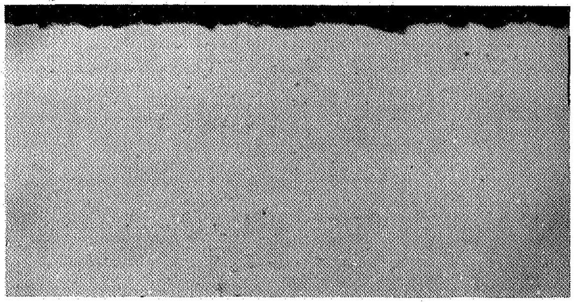


(3) Electron beam weld: some agglomeration of dispersion, some porosity; note second broad shallow "cosmetic" pass to seal porosity, fine grain weld. 50X

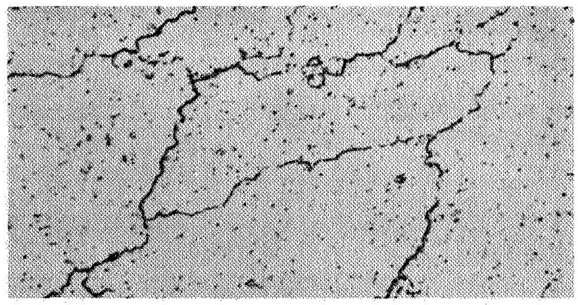


(4) Surface oxides: 1400°F, 1800°F, 2000°F, 2100°F, adherent; 2200°F, no heavy scale. 1.5X

Figure A3-3 Alloy TD Nickel-Chromium

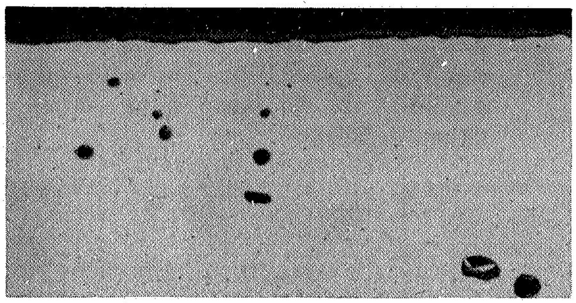


1600°F

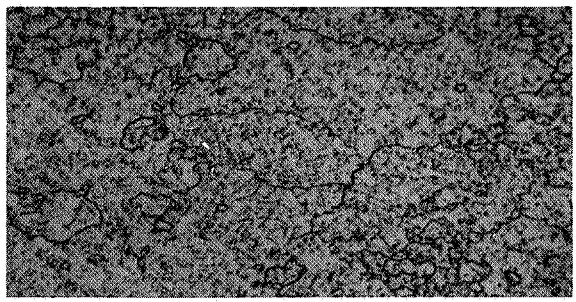


0.00005 inch

no change observed at 500X

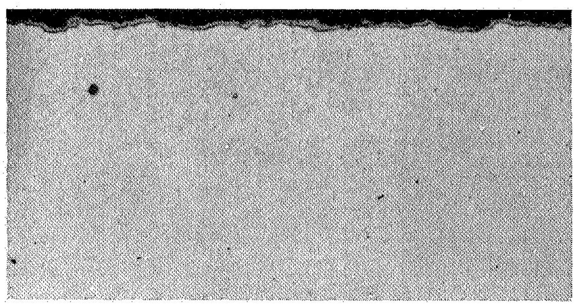


2000°F

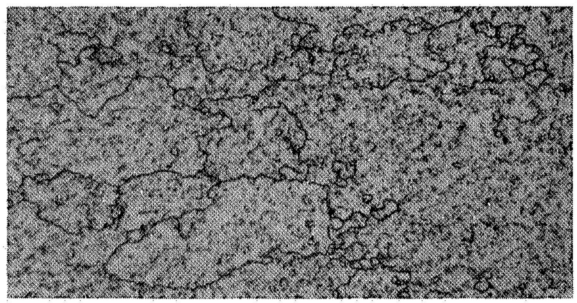


0.0001 inch

no change observed at 500X

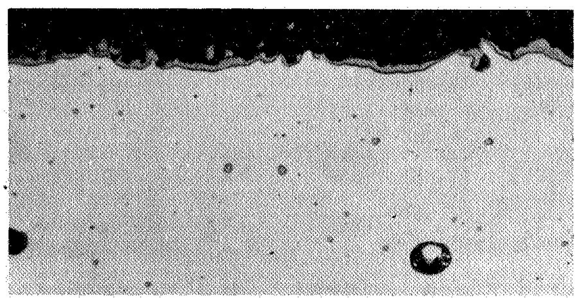


2100°F

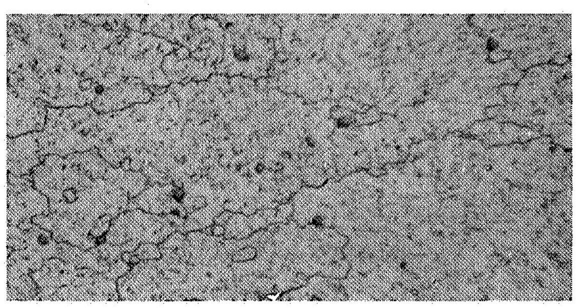


about 0.0002 inch
some scaling observed

little change



2200°F



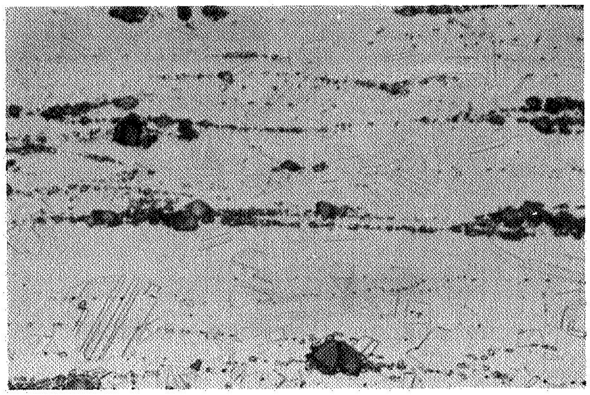
0.0003 inch plus subsurface oxidation

some agglomeration, no grain growth

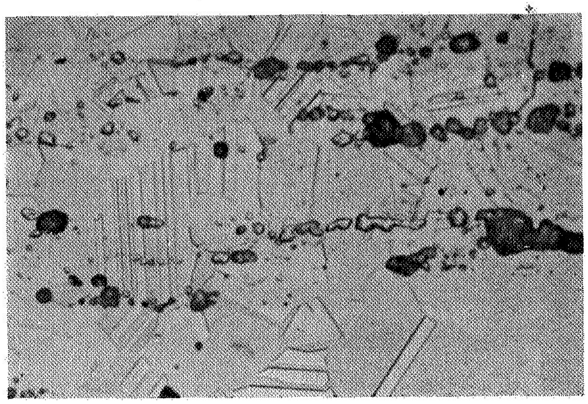
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

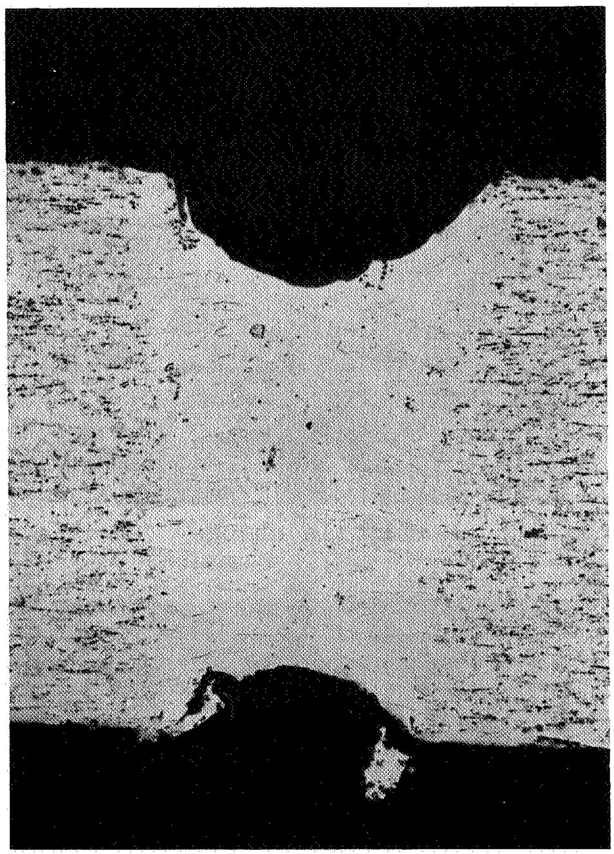
Figure A3-3 Alloy TD Nickel-Chromium



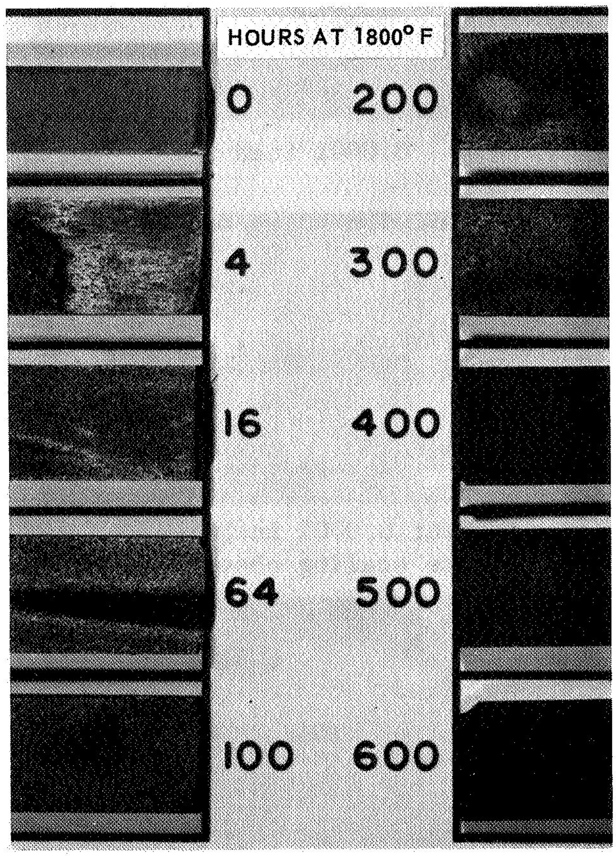
(1) As-received: fine grain extrusion with three percent spinel. 500X



(2) Sintered: some grain growth, much of spinel pulled out or etched out in sample preparation. 500X



(3) Electron beam weld: sound weld with low porosity, spinel expelled from weld zone. 50X



(4) Surface oxides: 1400°F, samples not available in time for test; 1600°F, adherent; 1800°F, 2000°F, roughened, adherent; 2100°F, 2200°F, roughened, adherent, specimen grew. 1.5X

Figure A3-4 Alloy Bendel 65-35

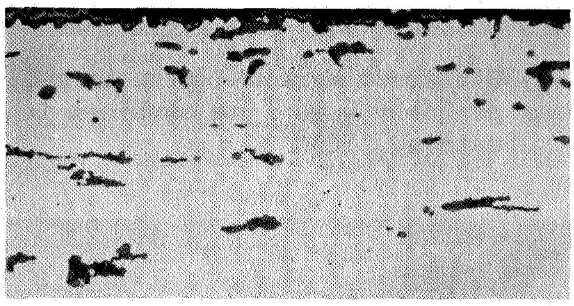
1400°F

A second lot of material was prepared for 2000°F tests. Extrusion direction of 1800 and 2000°F specimens is into photo; for 1600°F specimen it is across photo

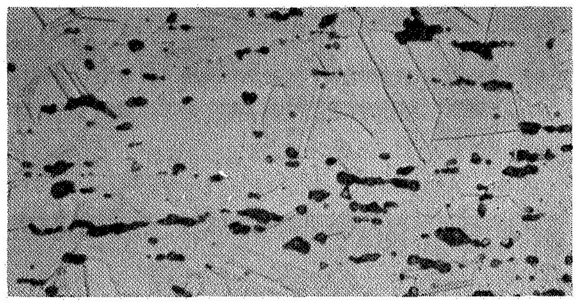
not tested

not tested

1600°F

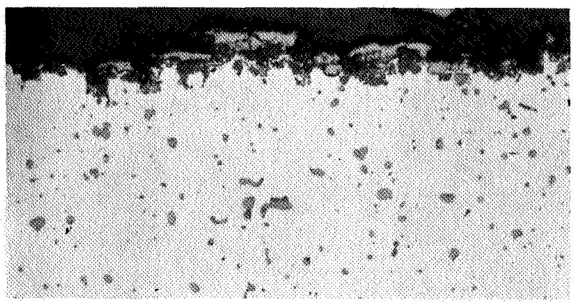


0.0002 inch

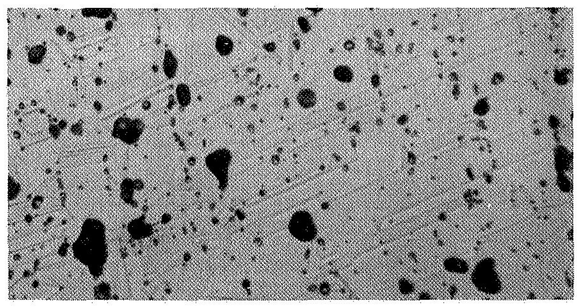


no change

1800°F

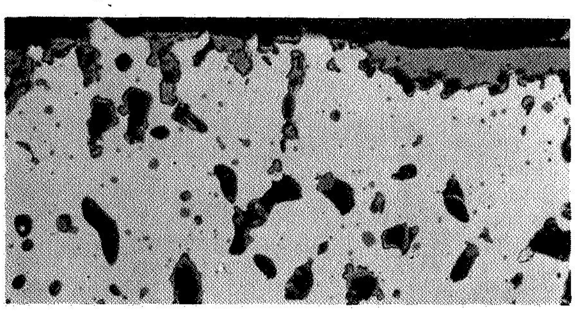


0.0003 inch, 0.0012 inch penetration

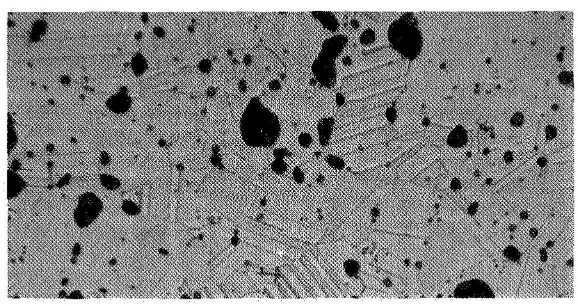


no change

2000°F



0.0003 inch, 0.004 inch penetration

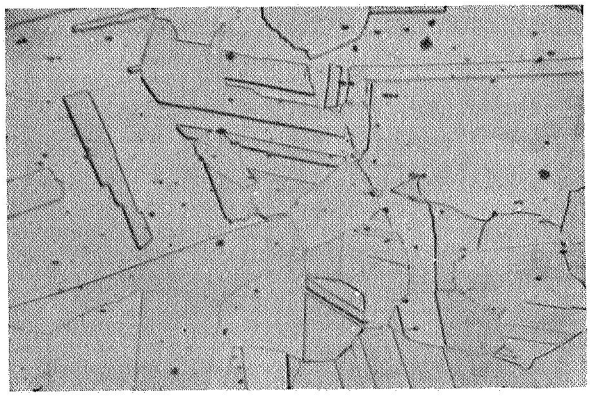


no change, larger particles of spinel

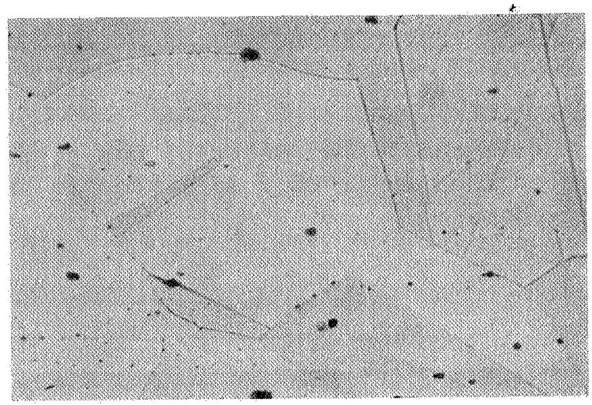
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

Figure A3-4 Alloy Bendel 65-35

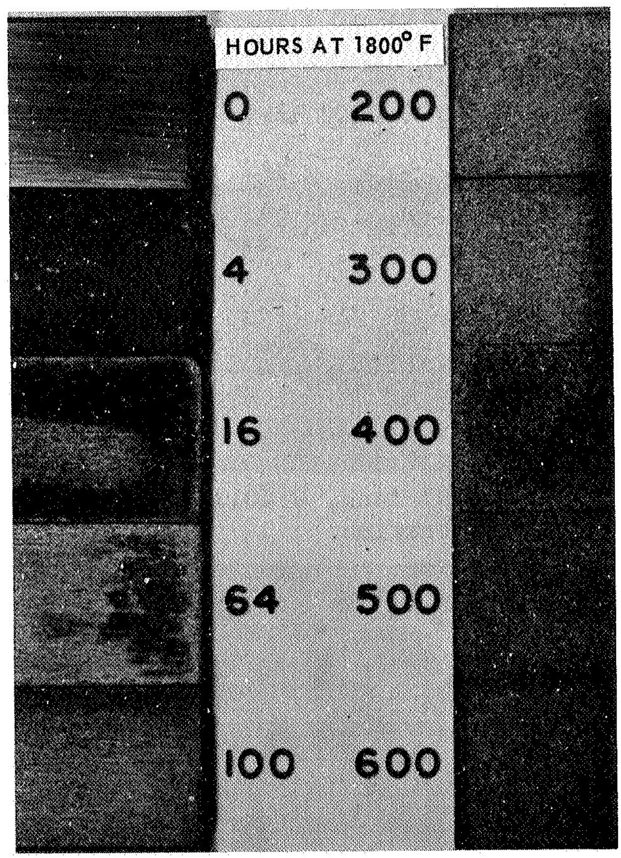


(1) As-received: medium grain size; some intergranular non-metallics. 500X



(2) Sintered: grains quite large, probably some fine carbides in matrix. 500X

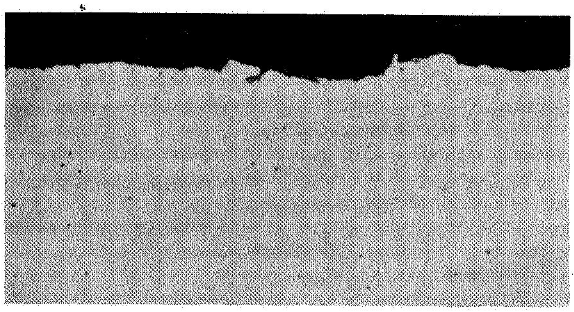
(3) Electron beam weld: sound weld, medium to fine grain. 500X



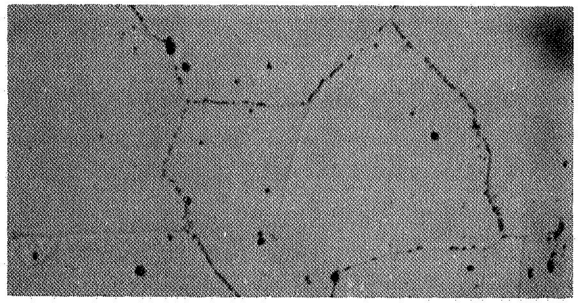
(4) Surface oxides: 1400°F, thin, adherent; 1600°F, roughening after 100 hours; 1800°F, 2000°F, roughened appearance after 16 hours. 1.5X

Figure A3-5 Alloy Chromel A

1400°F

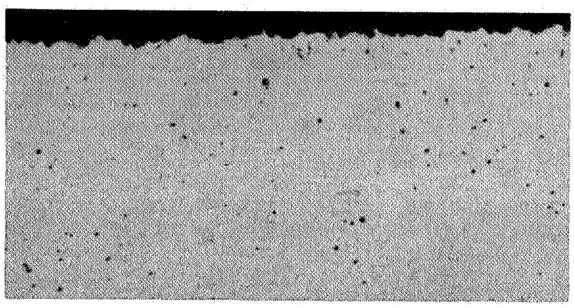


0.00005 inch

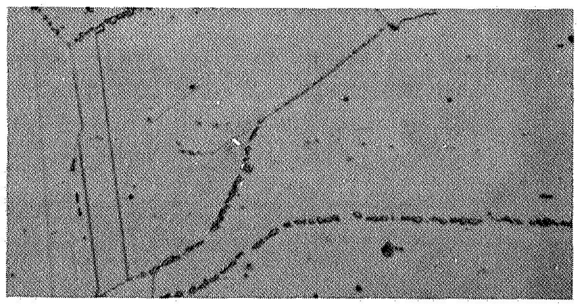


carbide precipitation in grain boundary

1600°F

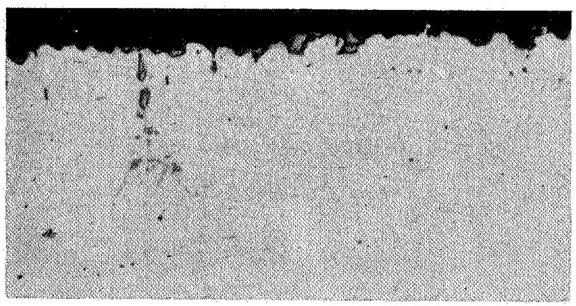


about 0.0001 inch

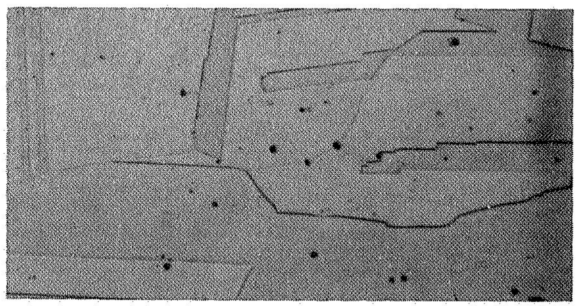


more pronounced grain boundary precipitate

1800°F

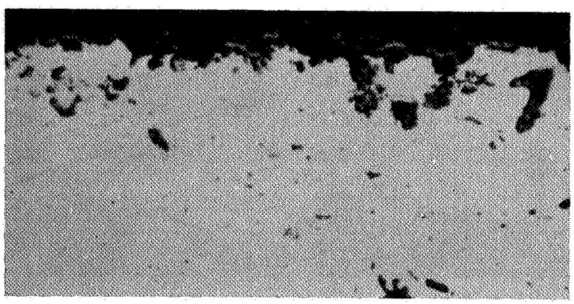


0.004 inch intergranular penetration

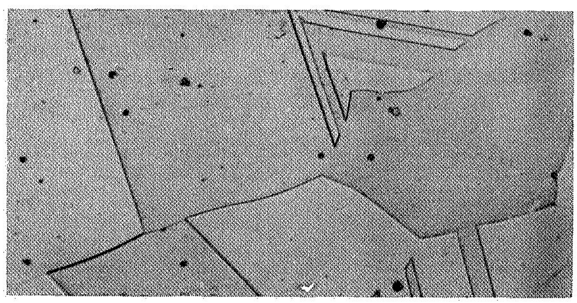


no boundary precipitate, unchanged from sintered material

2000°F



0.006 inch penetration, some sub-surface oxidation; original surface roughness about 0.0002 inch deep.

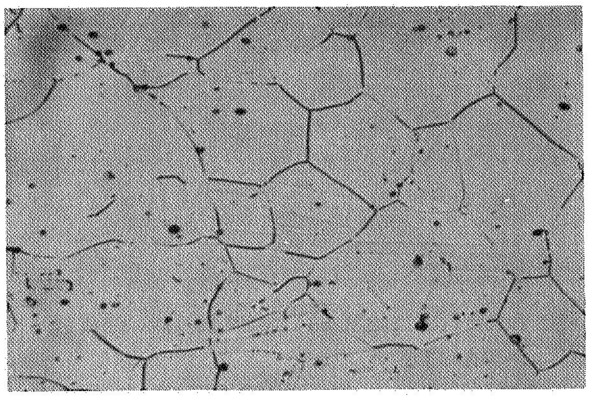


unchanged from sintered material

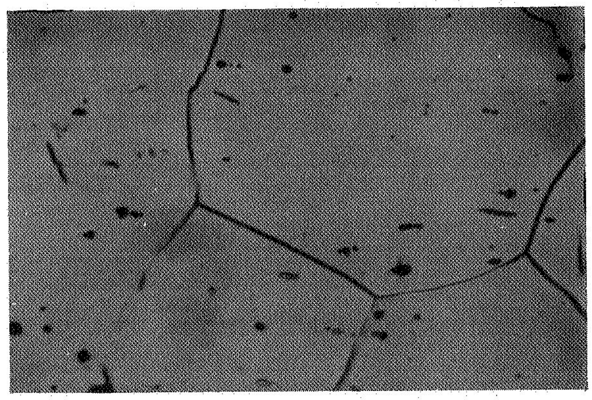
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

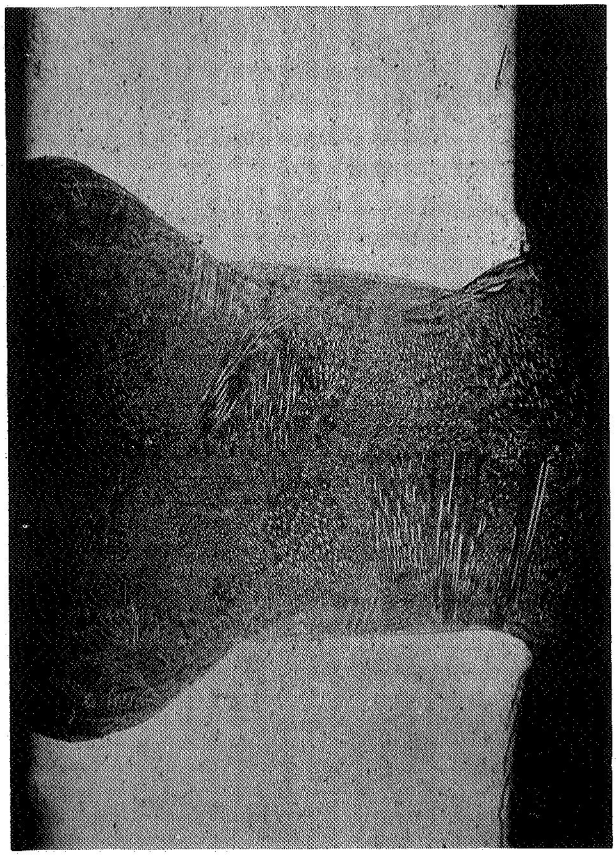
Figure A3-5 Alloy Chromel A



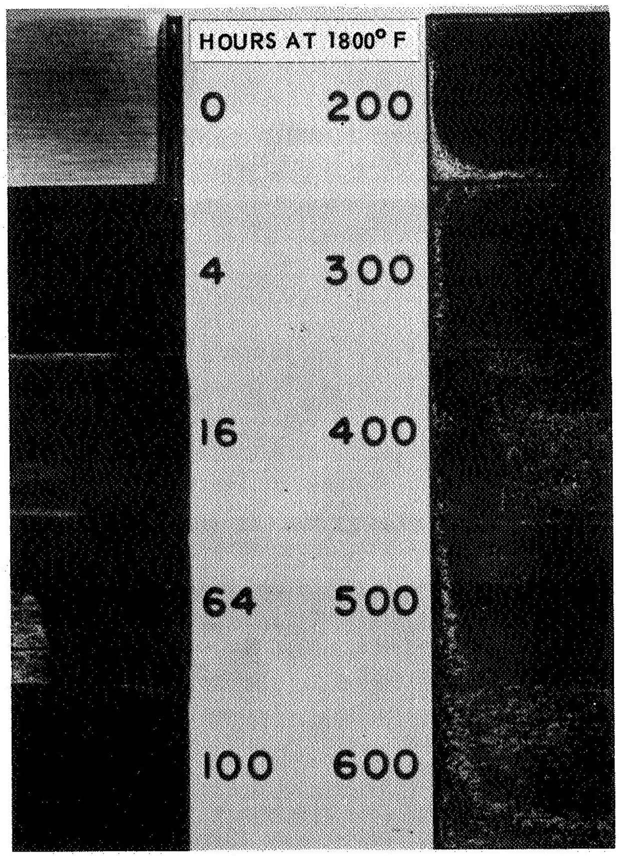
(1) As-received; medium grain size with non-metallic inclusions. 500X



(2) Sintered: some grain growth. 500X



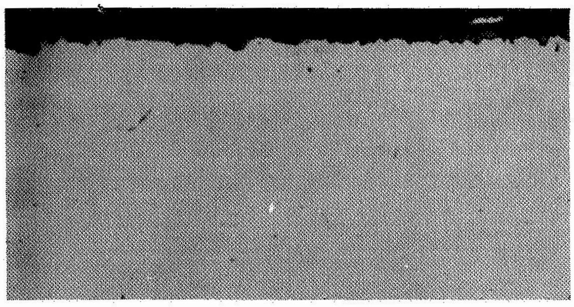
(3) Electron beam weld: very fine as-cast structure. 50X



(4) Surface oxides: 1400°F, thin adherent; 1600°F, heavier, adherent; 1800°F, coarsens after 300 hours; 2000°F, coarsens after 64 hours; 2100°F, flaking after 16 hours; 2200°F, severe erosion. 1.5X

Figure A3-6 Alloy DH242

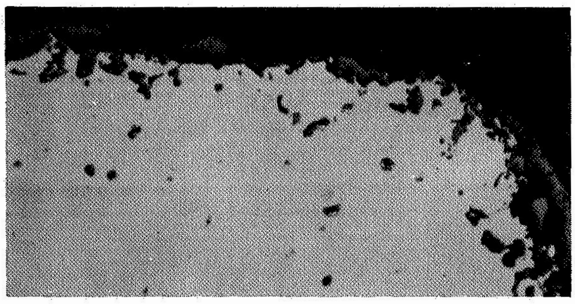
1600°F



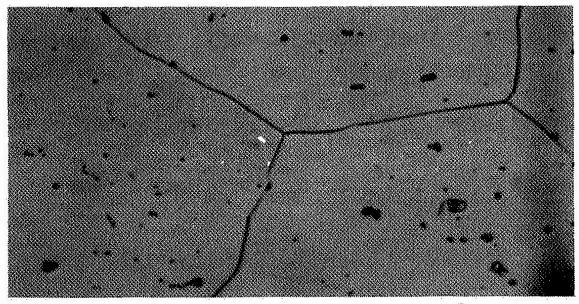
0.0002 inch

grain boundary carbide precipitate

1800°F

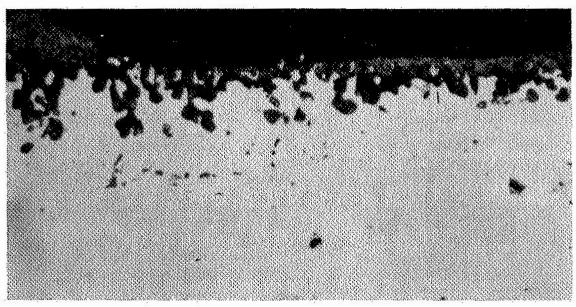


0.0004 inch, 0.0025 inch penetration

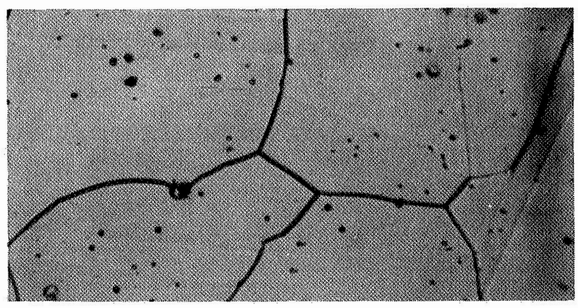


grain boundary carbide precipitate

2000°F

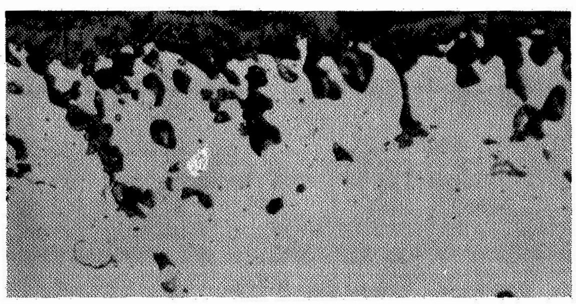


0.0005 inch, 0.006 inch penetration

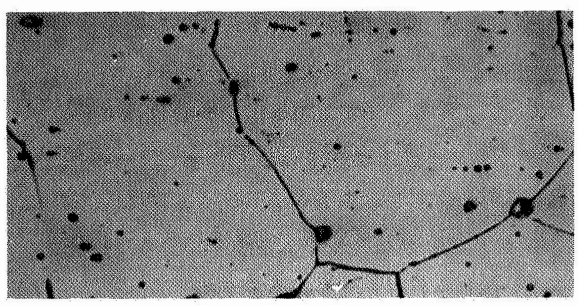


grain boundary carbide precipitate, little change from as-sintered

2100°F



0.0005 inch, 0.006 inch penetration plus subsurface oxides

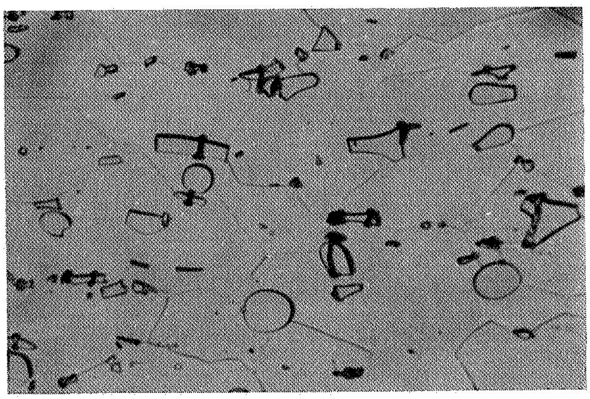


grain boundary carbide precipitate, little change from as sintered

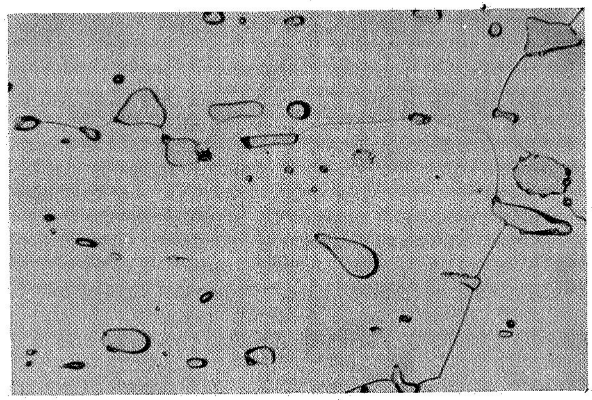
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

Figure A3-6 Alloy DH242

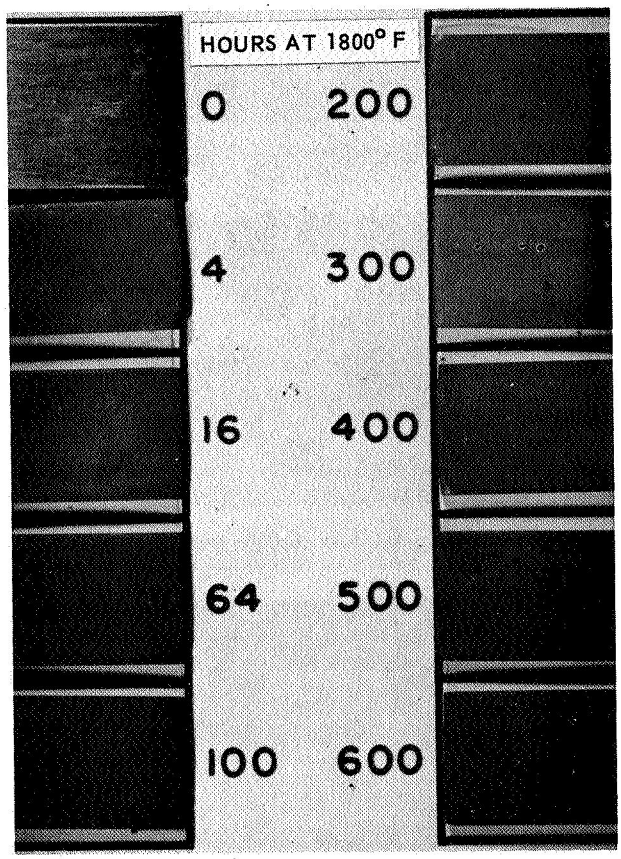


(1) As-received: matrix with intermetallic second phase. 500X



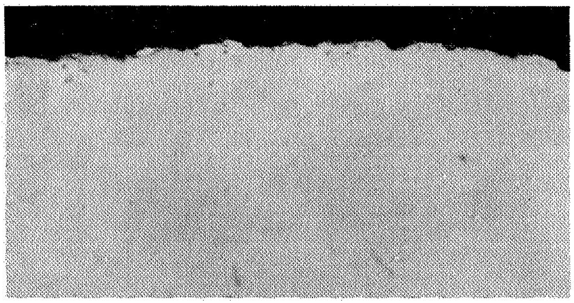
(2) Sintered: some grain growth, somewhat lesser amount of second phase. 500X

(3) Electron beam weld: sound, fine grained weld. 50X

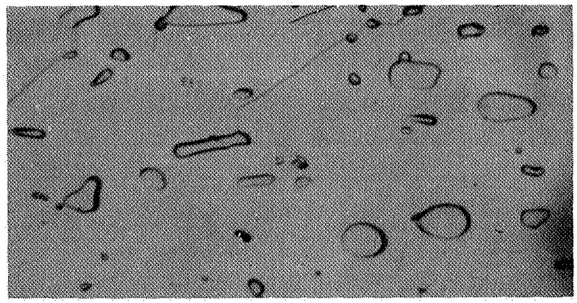


(4) Surface oxides: 1400°F, 1600°F, thin adherent; 1800°F, heavier, adherent; 2000°F, coarsening at 500 hours. 1.5X

Figure A3-7 Alloy GE 1541

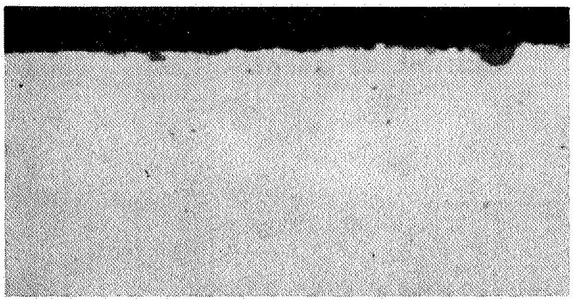


1400°F

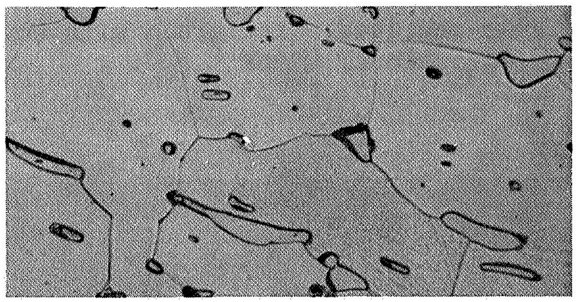


<0.0001 inch

unchanged from sintered condition

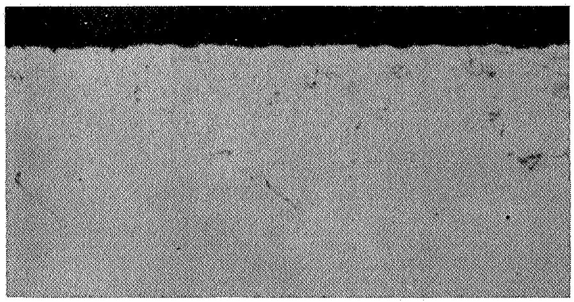


1600°F

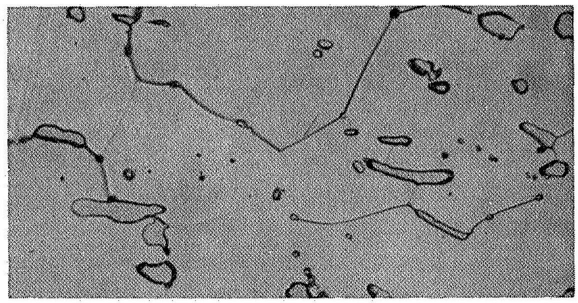


about 0.0001 inch

unchanged from sintered condition

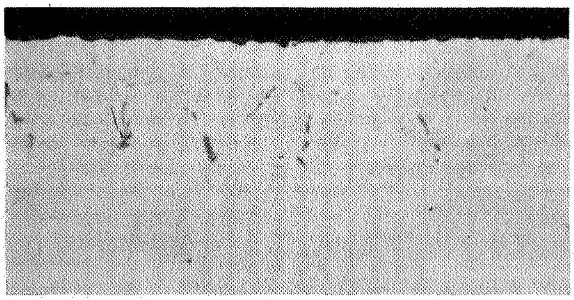


1800°F

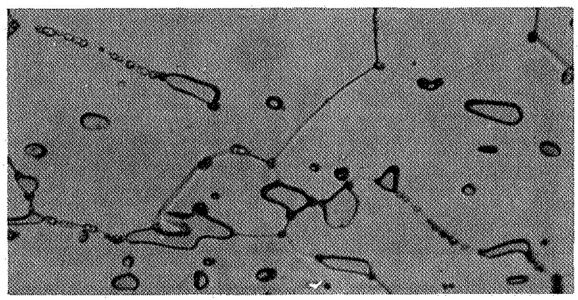


0.00015 inch plus 0.0045 inch penetration

unchanged from sintered condition



2000°F



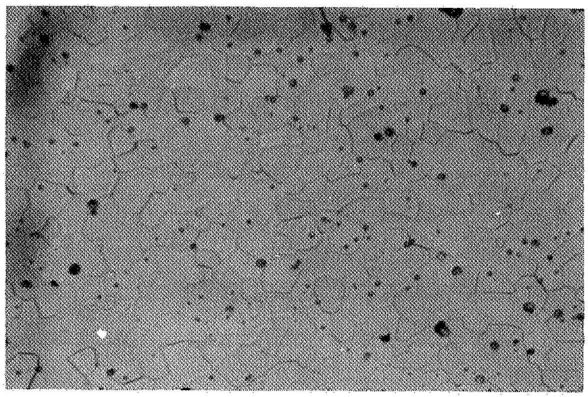
0.0003 inch plus 0.0045 penetration

some grain boundary precipitate

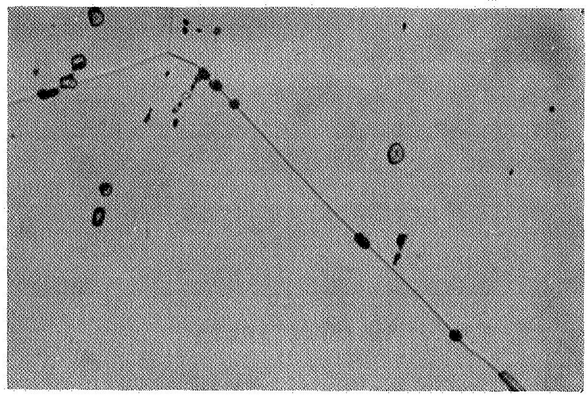
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

Figure A3-7 Alloy GE 1541

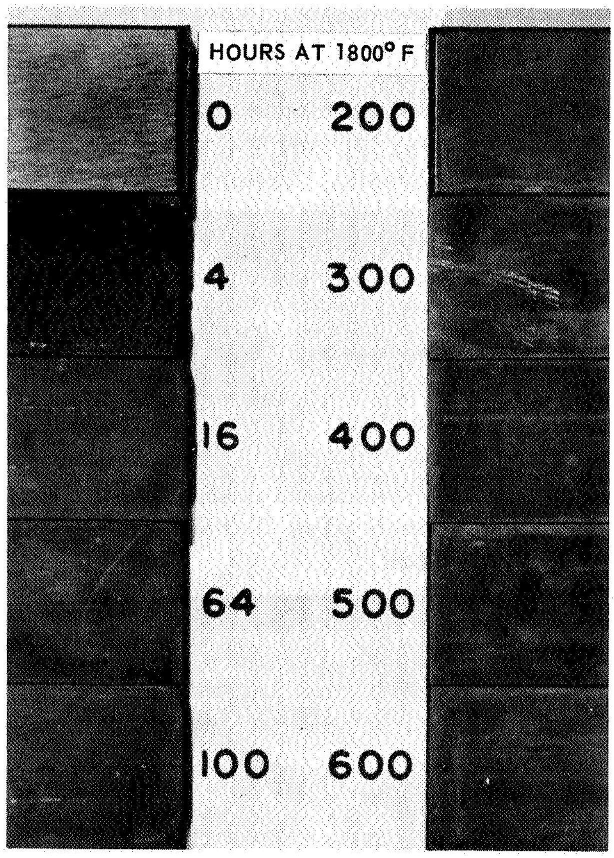


(1) As-received: fine grain with some inclusions. 500X



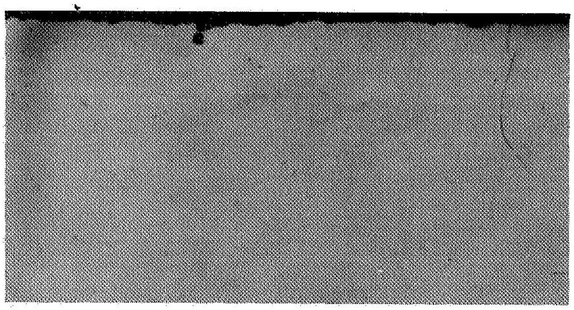
(2) Sintered: large grains, small amount of second phase. 500X

(3) Electron beam weld: very fine grain weld zone, some lack of fusion at bottom of weld. 50X



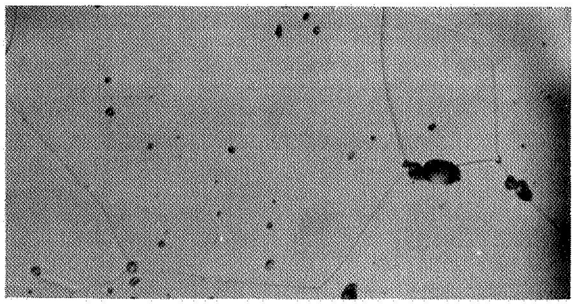
(4) Surface oxides: 1400°F, 1600°F, 1800°F, 2000°F, thin, adherent; 2100°F, slight coarsening; 2200°F, little change. 1.5X

Figure A3-8 Alloy Hoskins 875

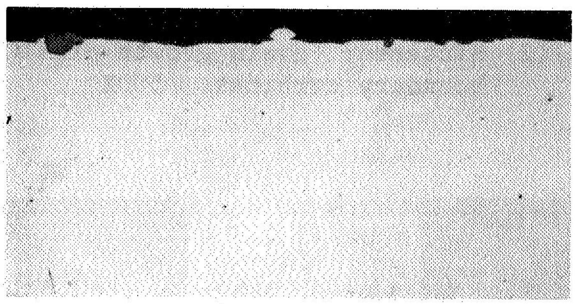


0.0003 inch

1600°F

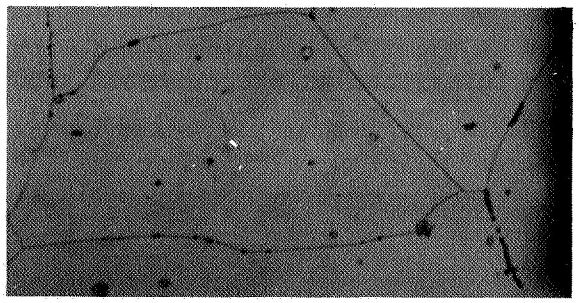


no change from sintered sample

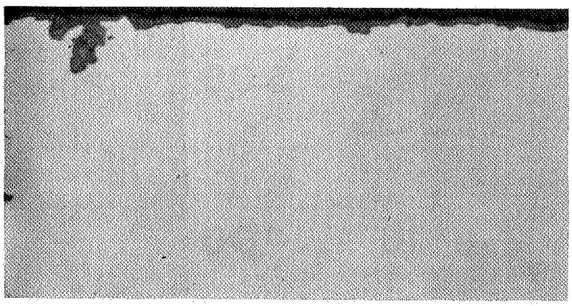


0.0002 inch

1800°F

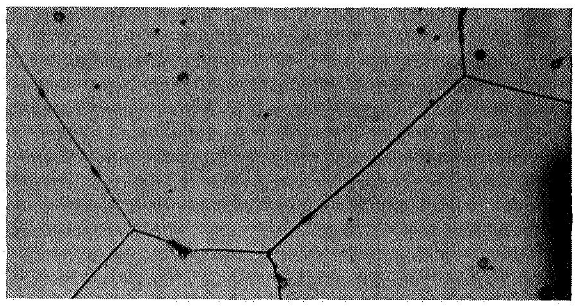


some grain boundary precipitation

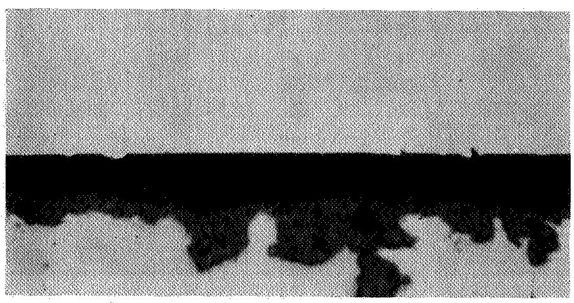


0.00015 inch

2000°F

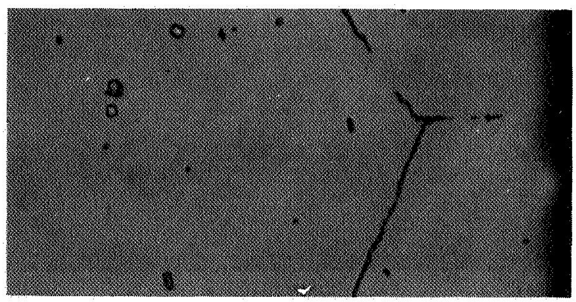


some second phase growth



0.0007 inch plus 0.005 inch penetration

2100°F

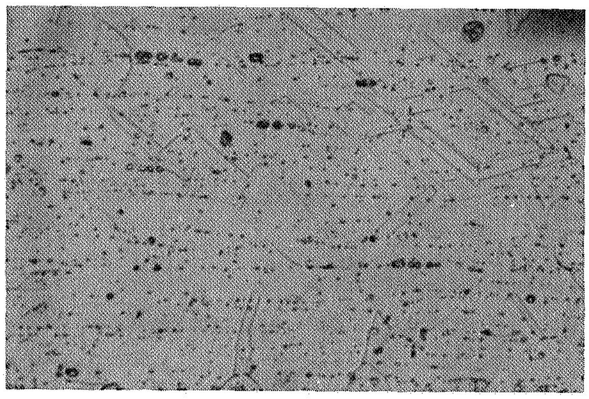


more grain boundary precipitate

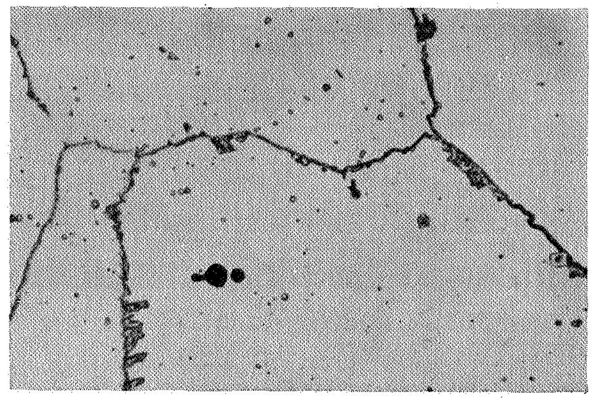
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

Figure A3-8 Alloy Hoskins 875

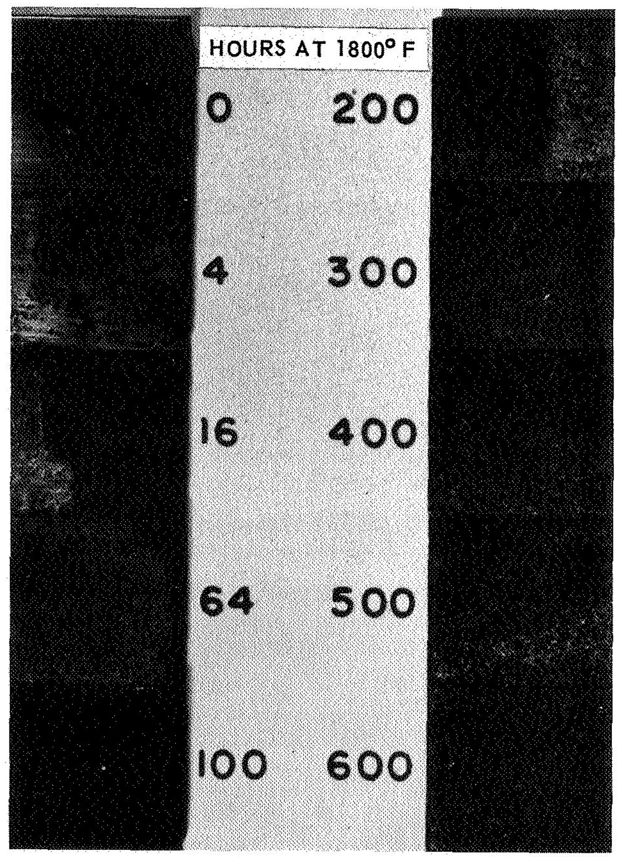


(1) As-received: medium grain with intergranular precipitate. 500X



(2) Sintered: grain growth plus boundary carbides. 500X

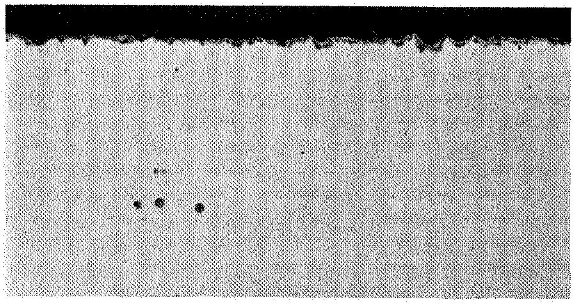
(3) Electron beam weld: sound, fine grained weld with fine precipitate. 50X



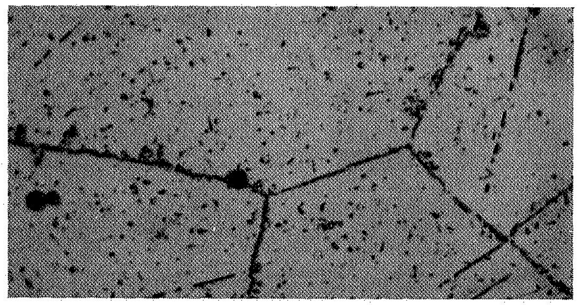
(4) Surface oxides: 1400°F - slight surface roughening after 300 hours; 1600°F - roughened at 100 hours; 1800°F - roughened at 16 hours; 2000°F - roughened with some flaking. 1.5X

Figure A3-9 Alloy RA 333

1400°F

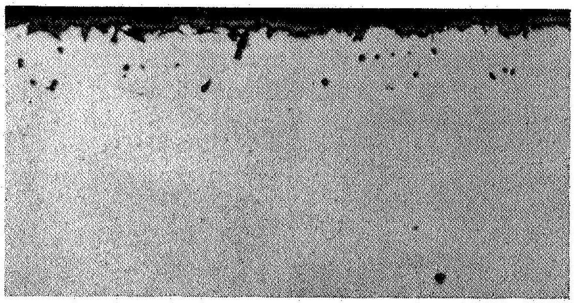


0.00015 inch

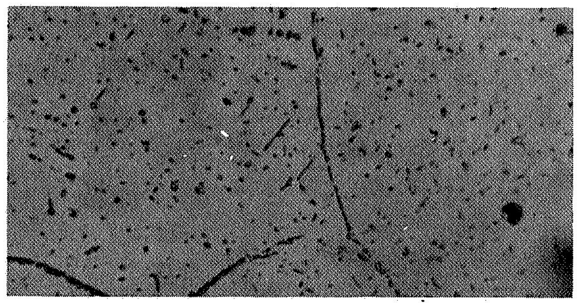


internal precipitation

1600°F

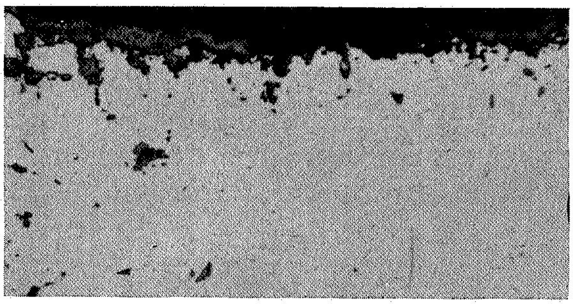


0.00035 inch, some subsurface oxides

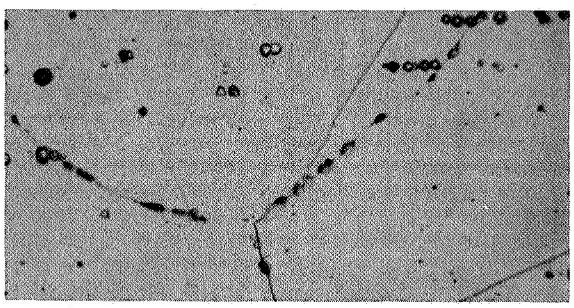


internal precipitation

1800°F

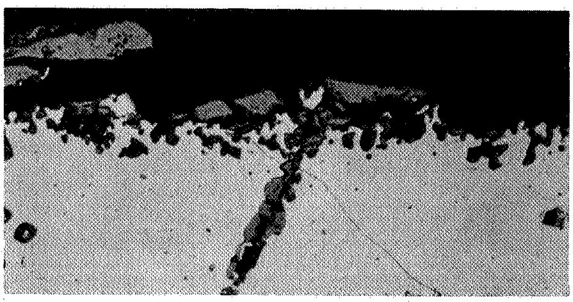


surface oxide flaking away, maximum penetration 0.0025 inch

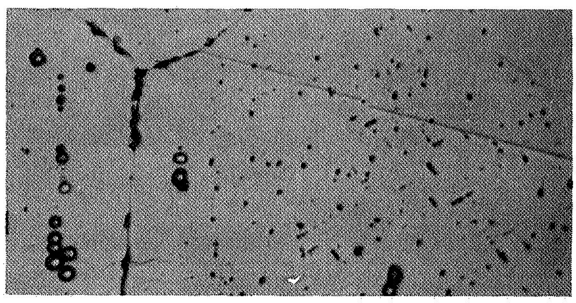


almost complete solid solution

2000°F



surface oxide flaking off; penetration reaches at least 0.006 inch, large subsurface oxides

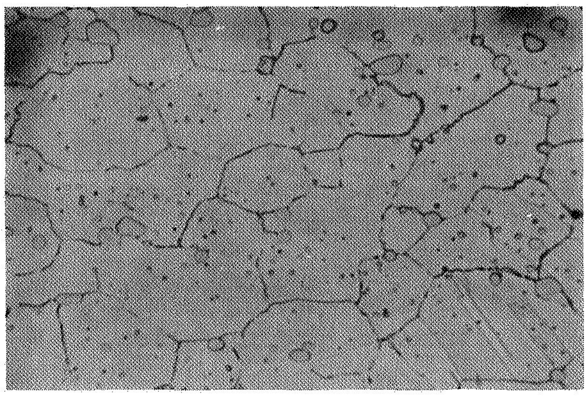


solid solution with some precipitate or internal oxidation.

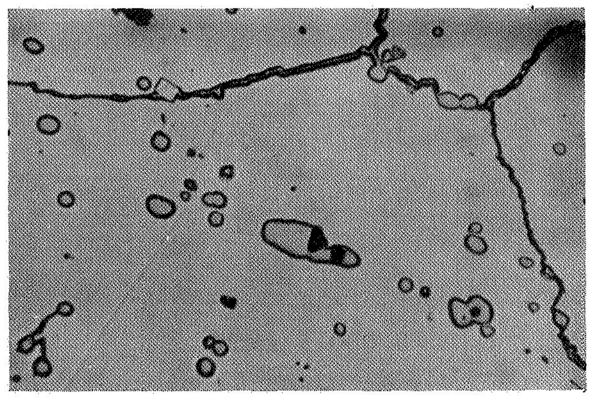
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

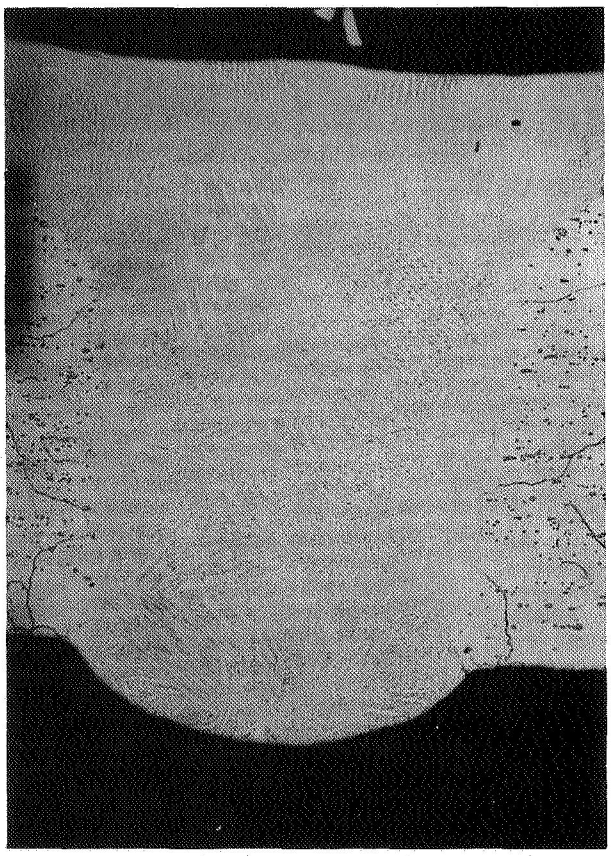
Figure A3-9 Alloy RA 333



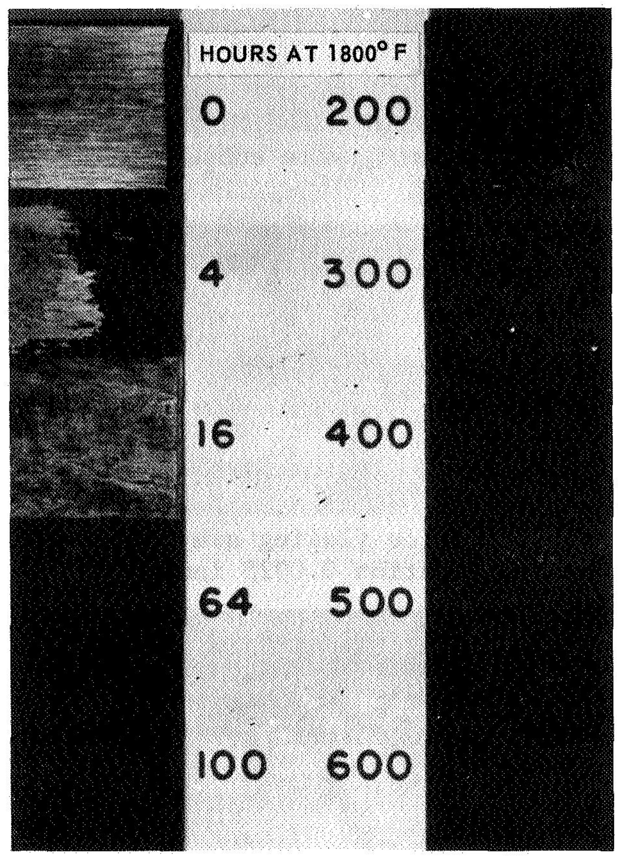
(1) As received: medium grain size with residual primary carbides. 500X



(2) Sintered: much larger grains, carbides have further spheroidized and agglomerated with grain boundaries emphasized. 500X



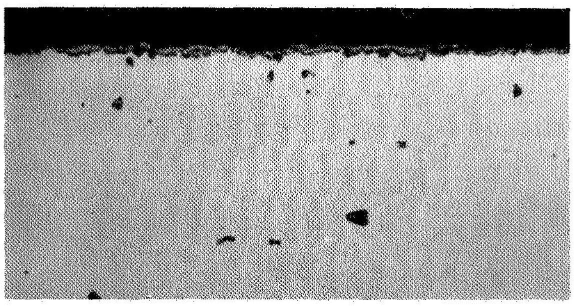
(3) Electron beam weld: very fine acicular, as-cast structure; sound weld. 50X



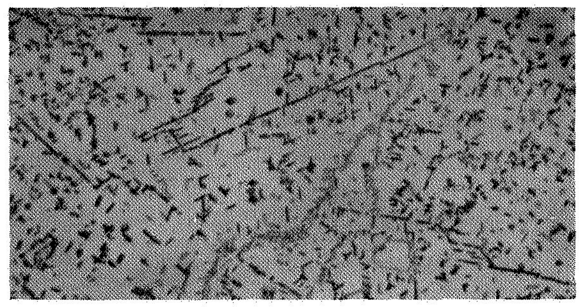
(4) Surface oxides: 1400°F - smooth, adherent; 1600°F - roughened after 16 hours; 1800°F - some flaking; 2000°F - rough; 2100°F - rougher; 2200°F - severe spalling after 200 hours. 1.5X

Figure A3-10 Alloy Hastelloy X

1600°F

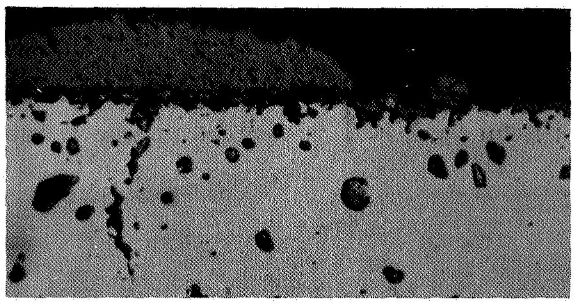


about 0.0002 inch, trace of subsurface oxide

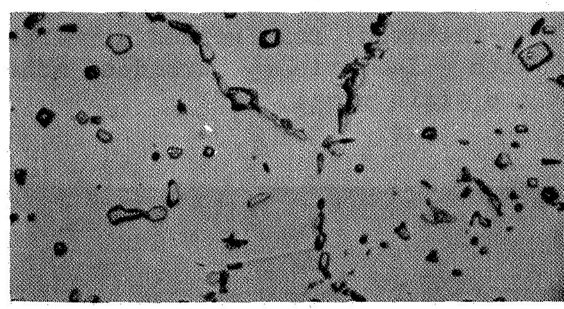


carbides have decomposed to yield laves (or mu) phase

1800°F

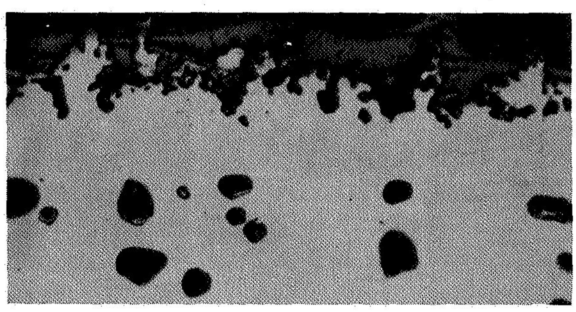


0.0002 inch, plus 0.003 inch penetration and subsurface oxidation

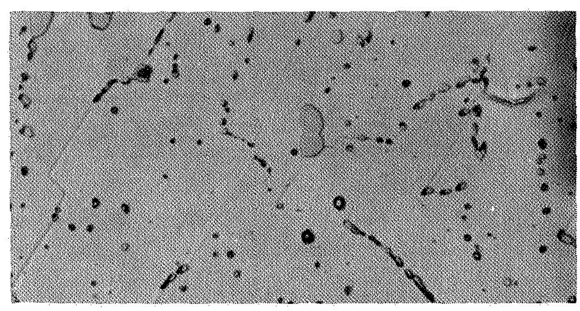


additional carbide precipitation

2000°F

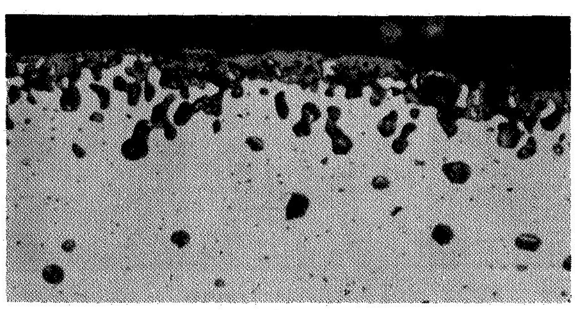


0.0003 inch, 0.005 inch penetration and subsurface oxidation

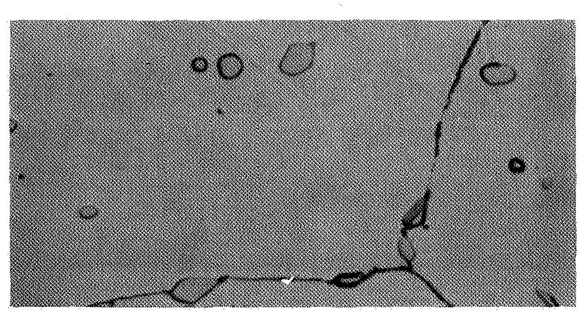


little change from sintered condition

2100°F



severe attack

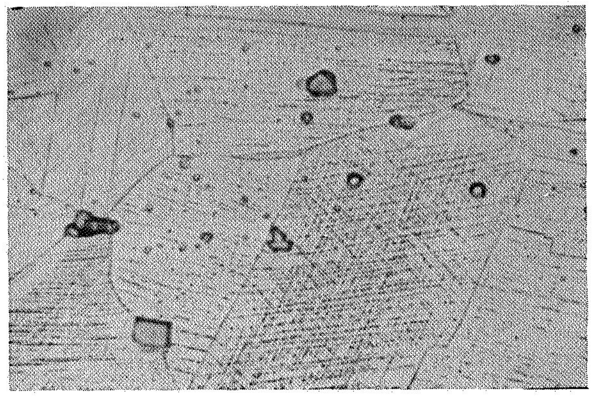


further carbide solution and homogenization

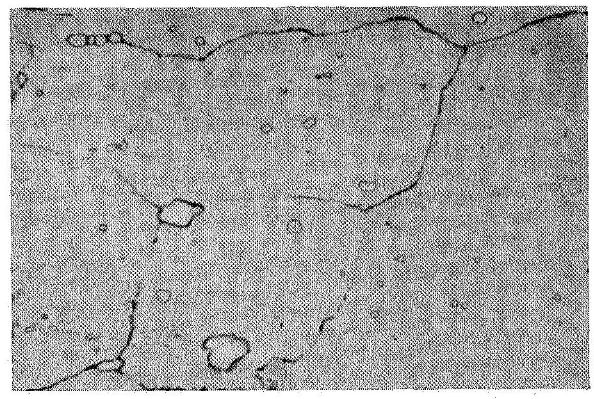
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

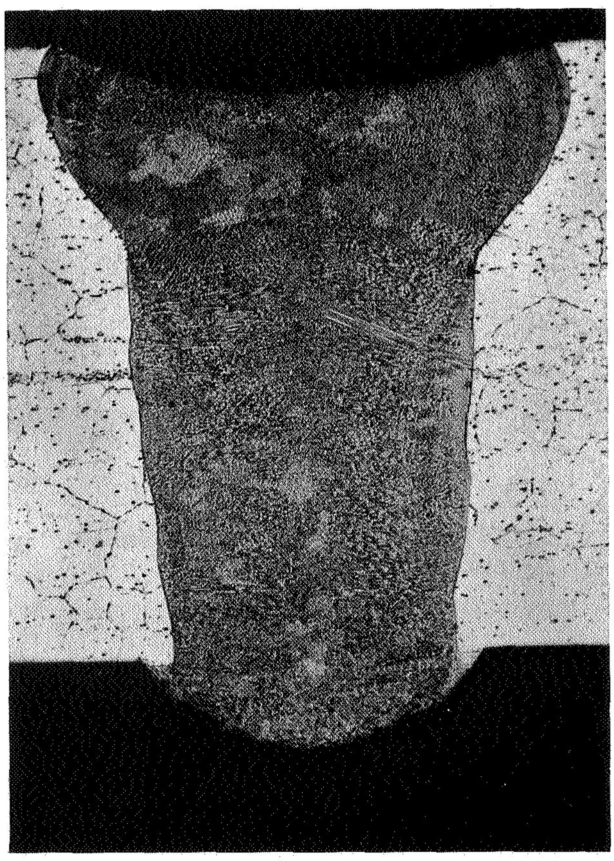
Figure A3-10 Alloy Hastelloy X



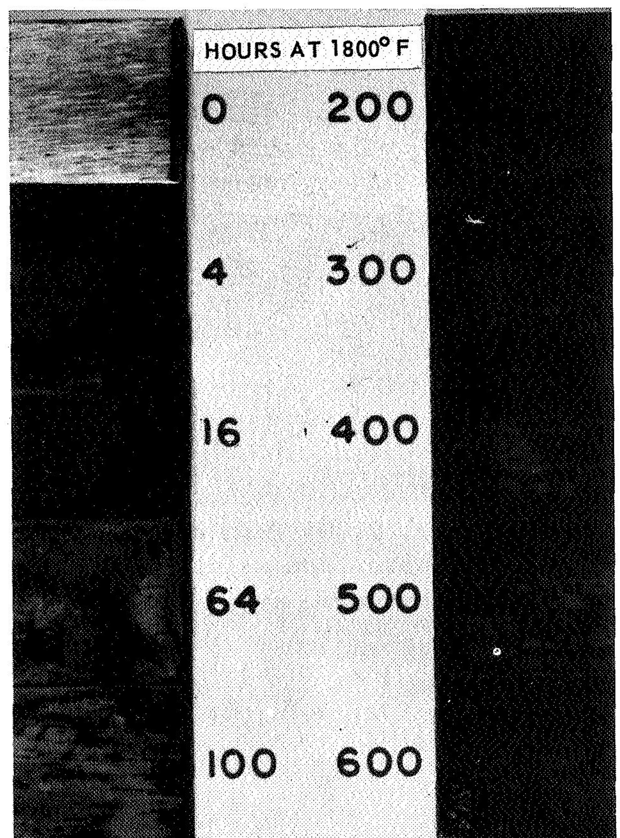
(1) As-received: cold worked structure with a few primary carbides, moderate grain size. 500X



(2) Sintered: recrystallized; little change in grain size, some carbides present plus unresolved fine precipitate, probably gamma prime. 500X

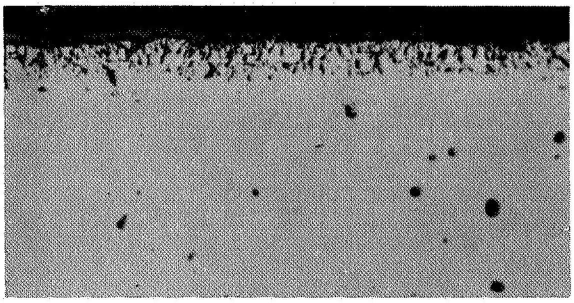


(3) Electron beam weld: sound weld, very fine as-cast structure with gamma prime. 50X

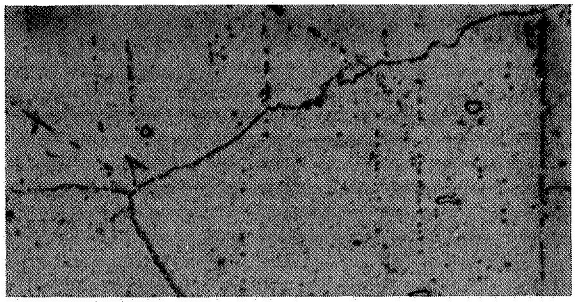


(4) Surface oxides: 1400°F - smooth, adherent; 1600°F - smooth, adherent; 1800°F - roughening; 2000°F - rougher; 2100°F - some edge attack at 200 hours; 2200°F - severe attack after 16 hours. 1.5X

Figure A3-11 Alloy Udimet 500

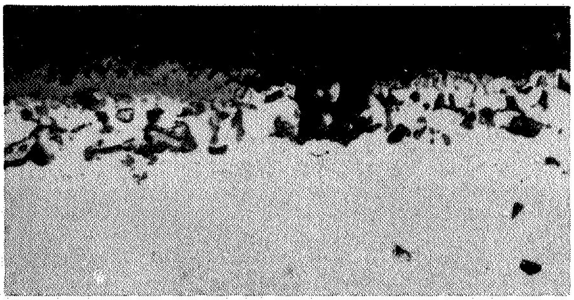


1600°F

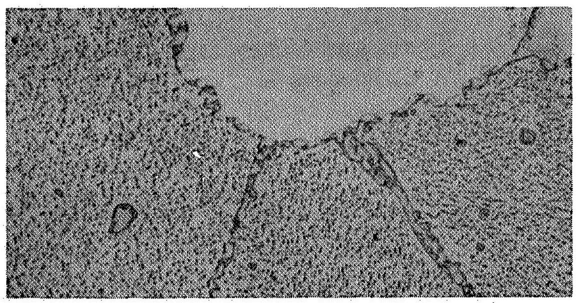


0.0003 inch, 0.001 inch penetration

fine precipitate of gamma prime and/or sigma

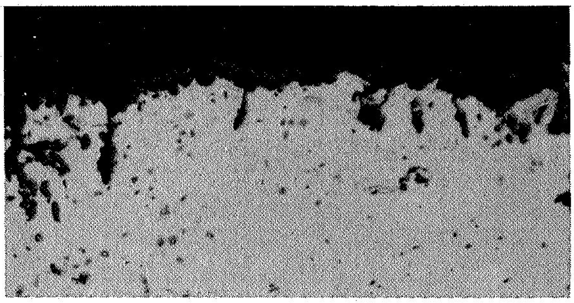


1800°F

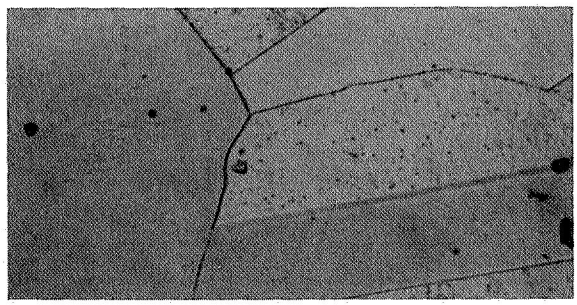


0.0005 inch, 0.001 with penetration

larger precipitate plus grain boundary carbides

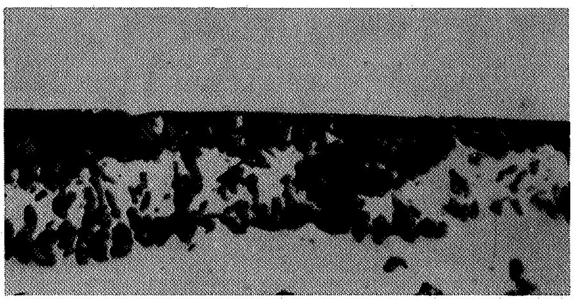


2000°F

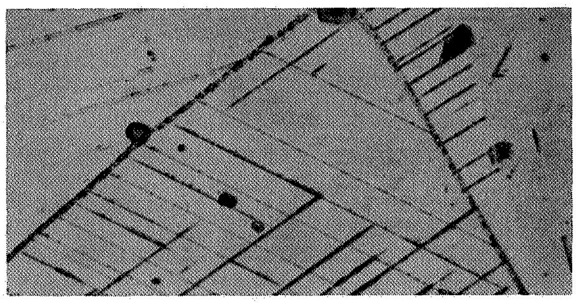


general attack with subsurface oxidation

unidentified fine precipitate, possibly sigma



2100°F



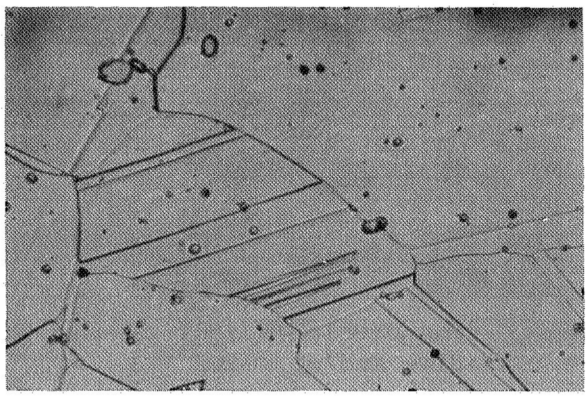
general attack with severe spalling

oriented acicular precipitate

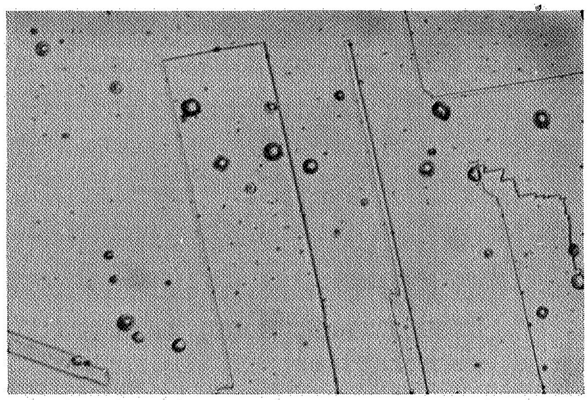
(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

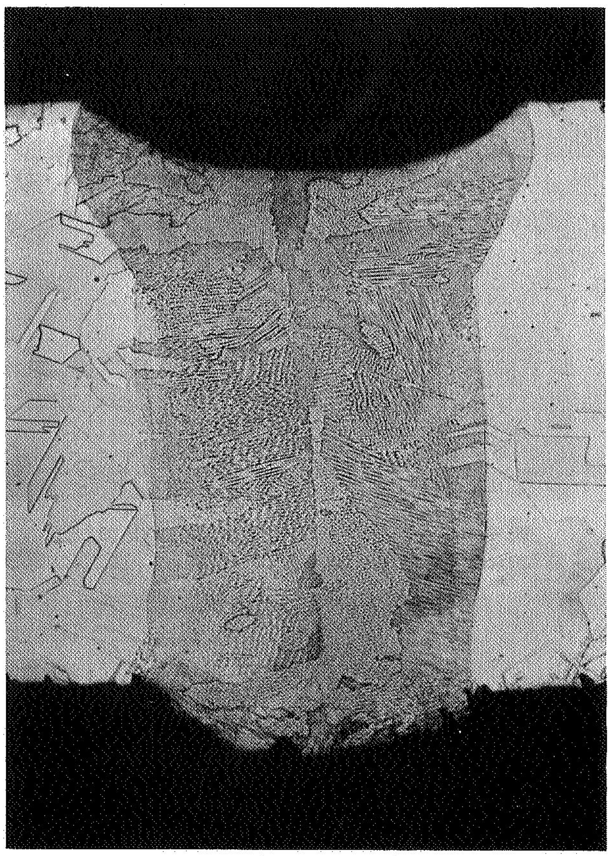
Figure A3-11 Alloy Udimet 500



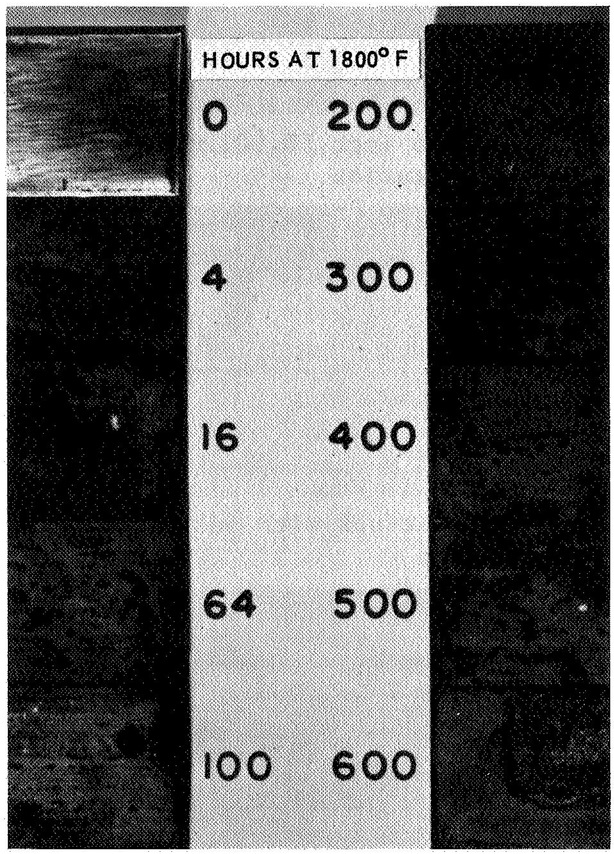
(1) As-received: medium grain size with twinning a few inclusions and/or carbides. 500X



(2) Sintered: some grain growth, but primarily single phase solid solution. 500X



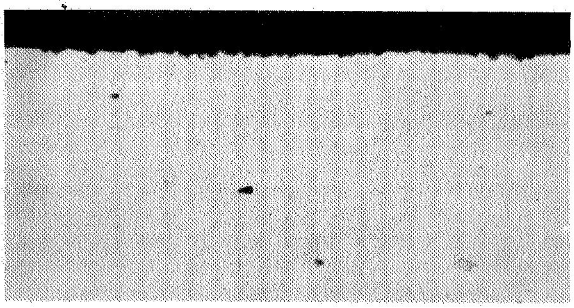
(3) Electron beam weld: sound weld, as-cast structure with very fine precipitate. 50X



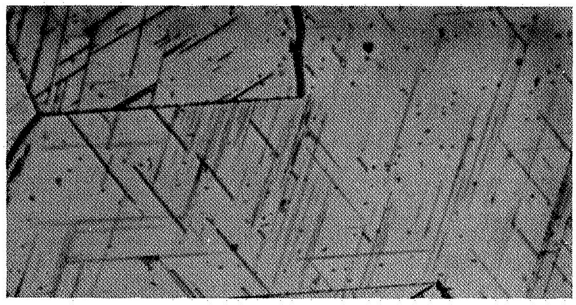
(4) Surface oxides: 1400°F - smooth, adherent; 1600°F - slightly roughened; 1800°F - roughened surface; 2000°F - flaking begins after 16 hours. 1.5X

Figure A3-12 Alloy Haynes 25 (L-605)

1400°F

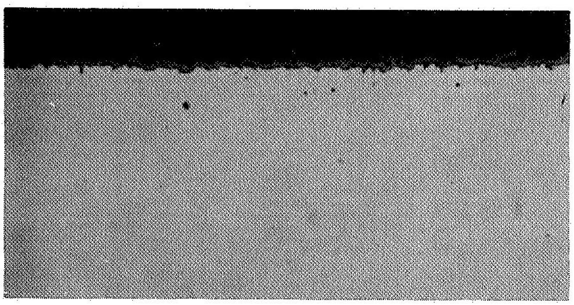


0.00005 inch

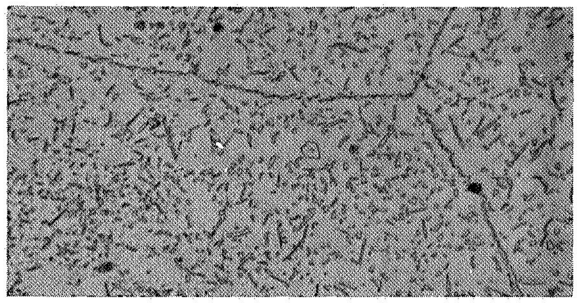


some grain boundary and internal carbide precipitation

1600°F



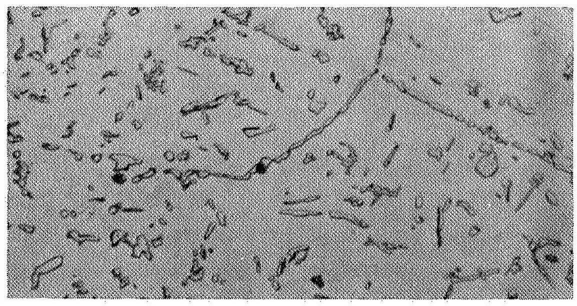
0.0002 inch, 0.0002 inch penetration



precipitates increased in volume

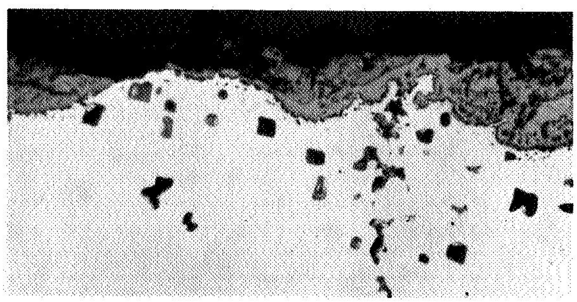
1800°F

0.0007 inch, 0.002 inch maximum penetration

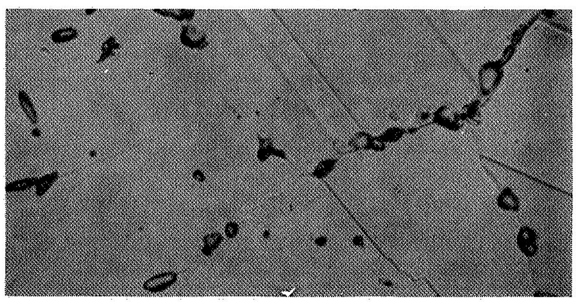


particles agglomerate

2000°F



erratic thickness, penetration reaches 0.0035 inch maximum



further growth in carbide size

(5) Oxide thickness at 600 hours exposure, unetched. 300X

(6) Internal structure at 600 hours exposure, etched. 500X

Figure A3-12 **Alloy Haynes 25 (L-605)**

APPENDIX 4
OXIDATION PENETRATION PLOTS

CONTENTS

ALLOY	FIGURE	PAGE
1. N 155	A4-1	122
2. TD nickel	A4-2	123
3. TD nickel-chromium	A4-3	124
4. Bendel 65-35	A4-4	125
5. Chromel A	A4-5	126
6. DH 242	A4-6	127
7. GE 1541	A4-7	128
8. Hoskins 875	A4-8	129
9. RA 333	A4-9	130
10. Hastelloy X	A4-10	131
11. Udimet 500	A4-11	132
12. Haynes 25	A4-12	133

Specimen thickness change (on one side only) and average oxide penetration depth are shown in relationship to the original metal surface as a function of exposure time for each temperature. Progressive increase in thickness (solid line) indicates specimen oxidation and growth. Decrease in thickness shows oxide spalling. Oxide penetration (dashed line) below the final surface represents uniform oxide layer growth plus average oxide growth into the metal. Oxide penetration may or may not extend below the initial surface depending on the relative thickness change and surface oxidation rates.

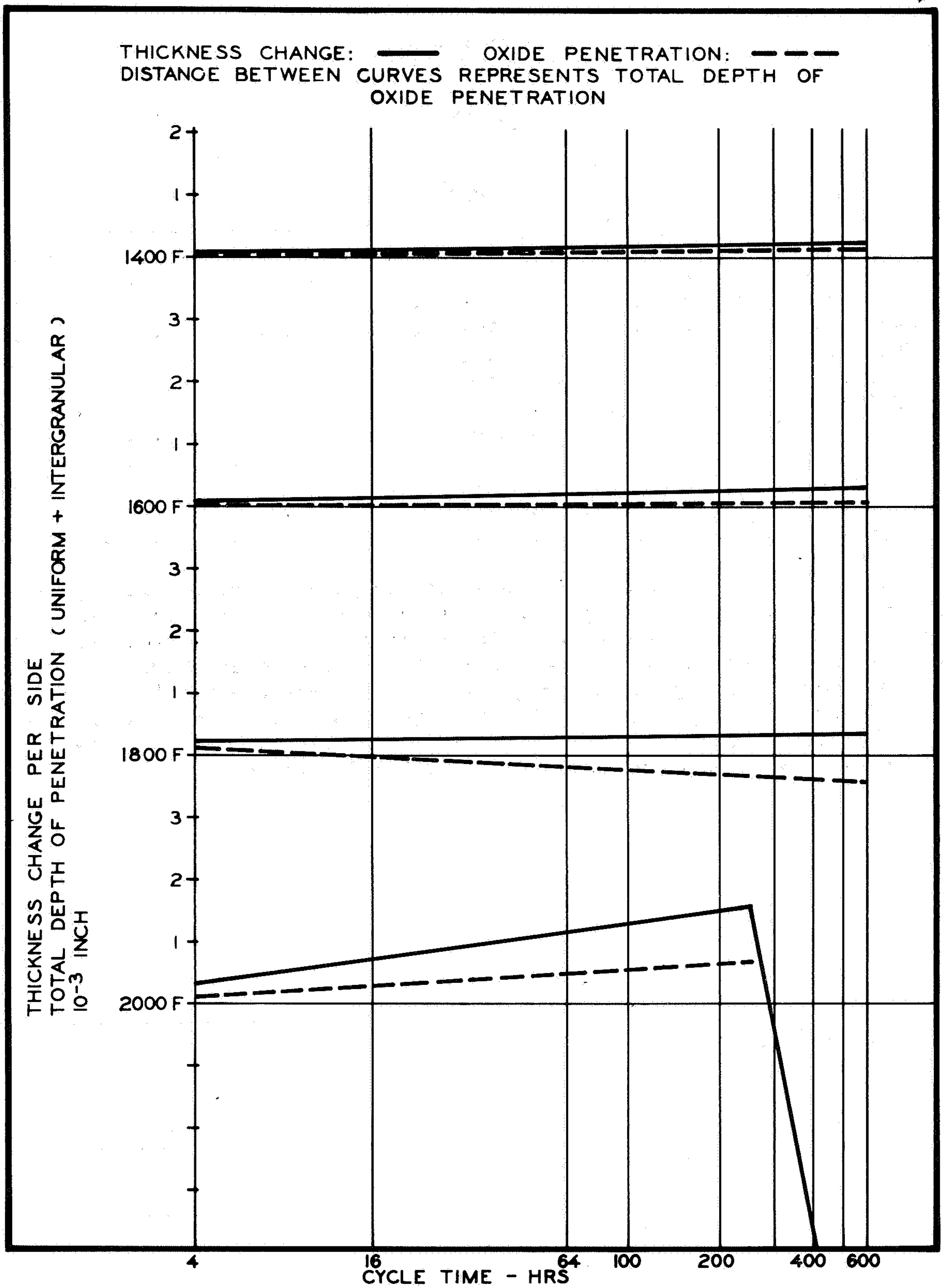


Figure A4-1 Oxidation penetration plot: Alloy 1, N 155.

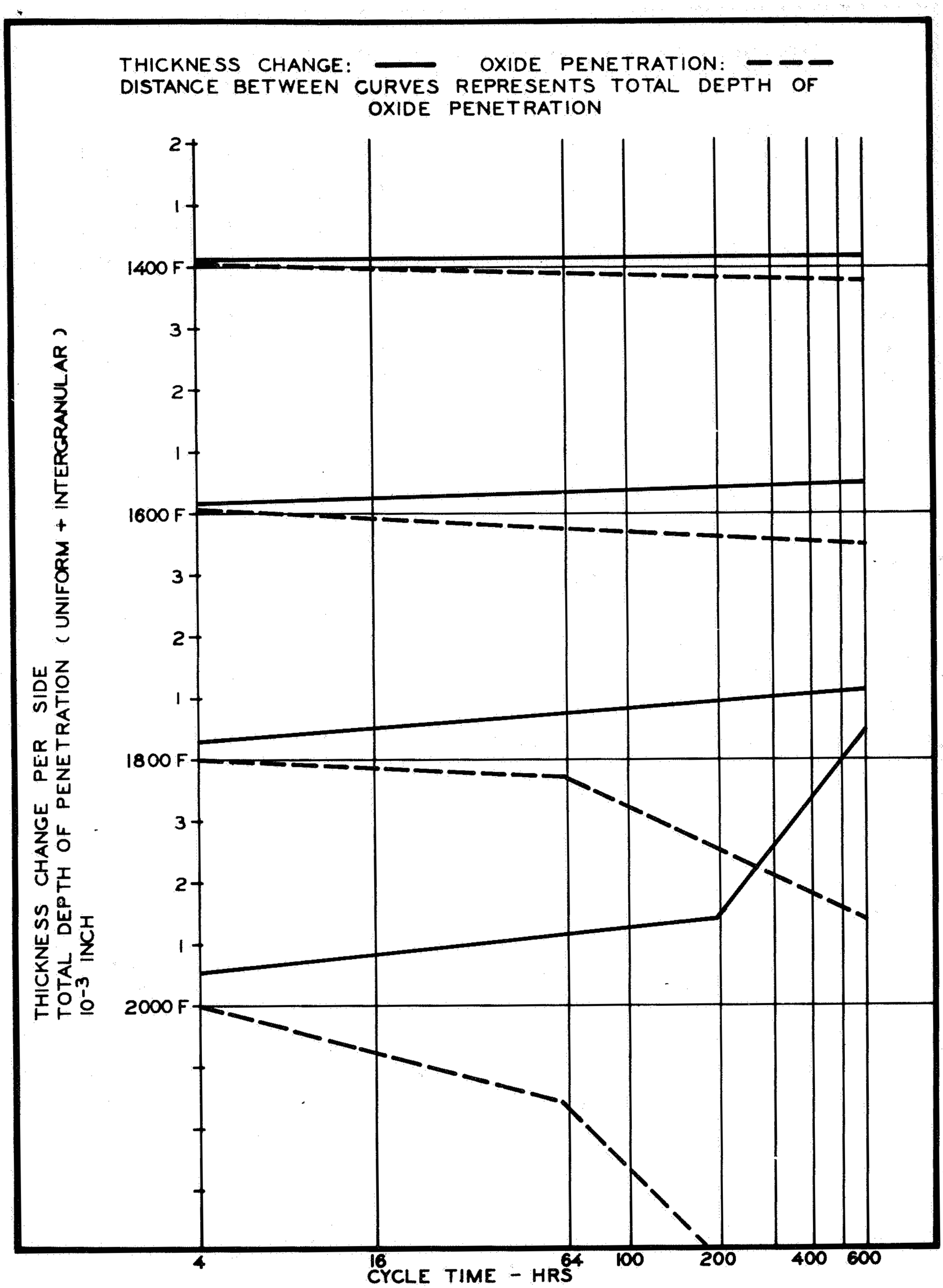


Figure A4-2 Oxidation penetration plot: Alloy 2, TD nickel.

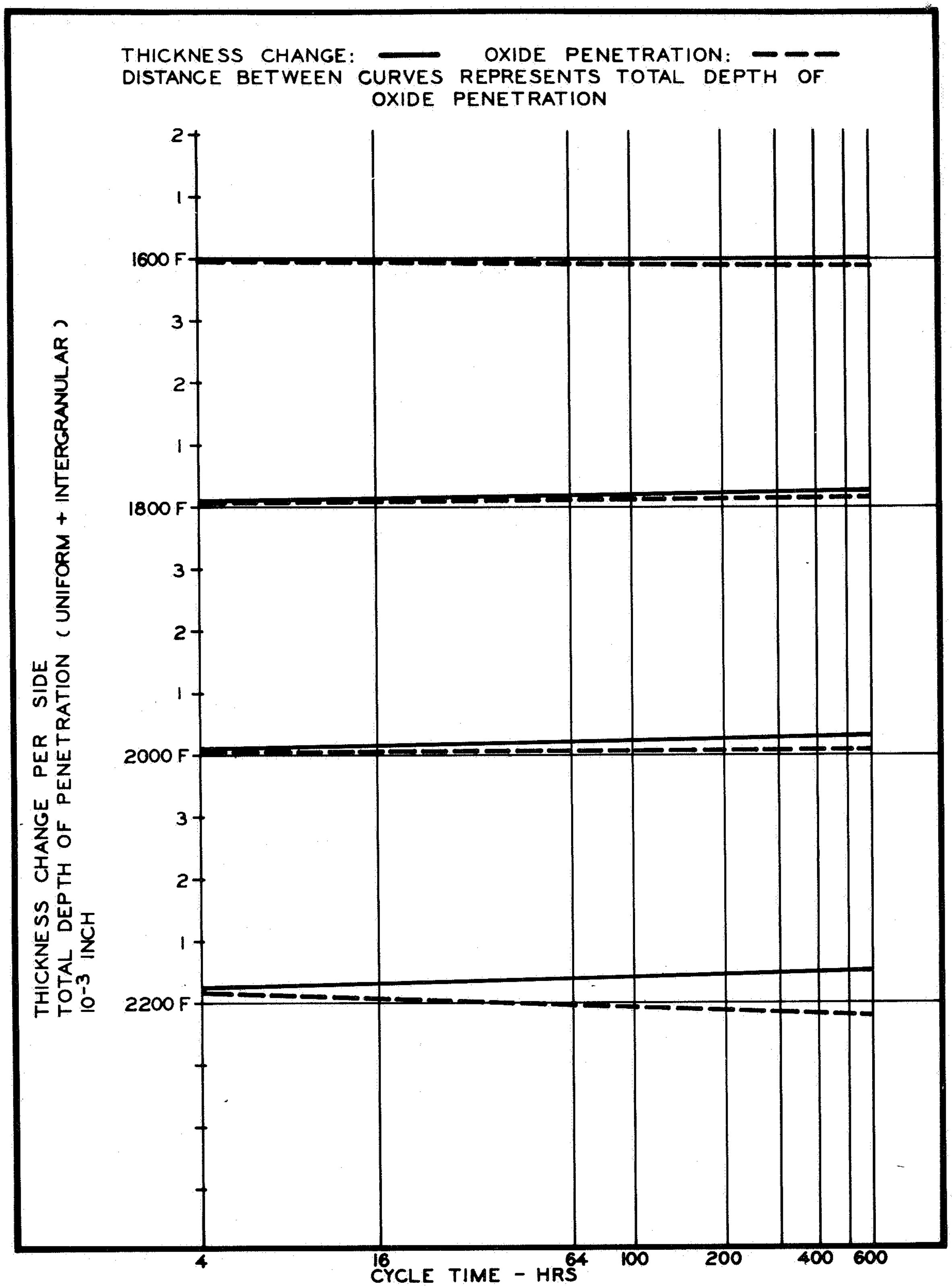


Figure A4-3 Oxidation penetration plot: Alloy 3, TD nickel-chromium.

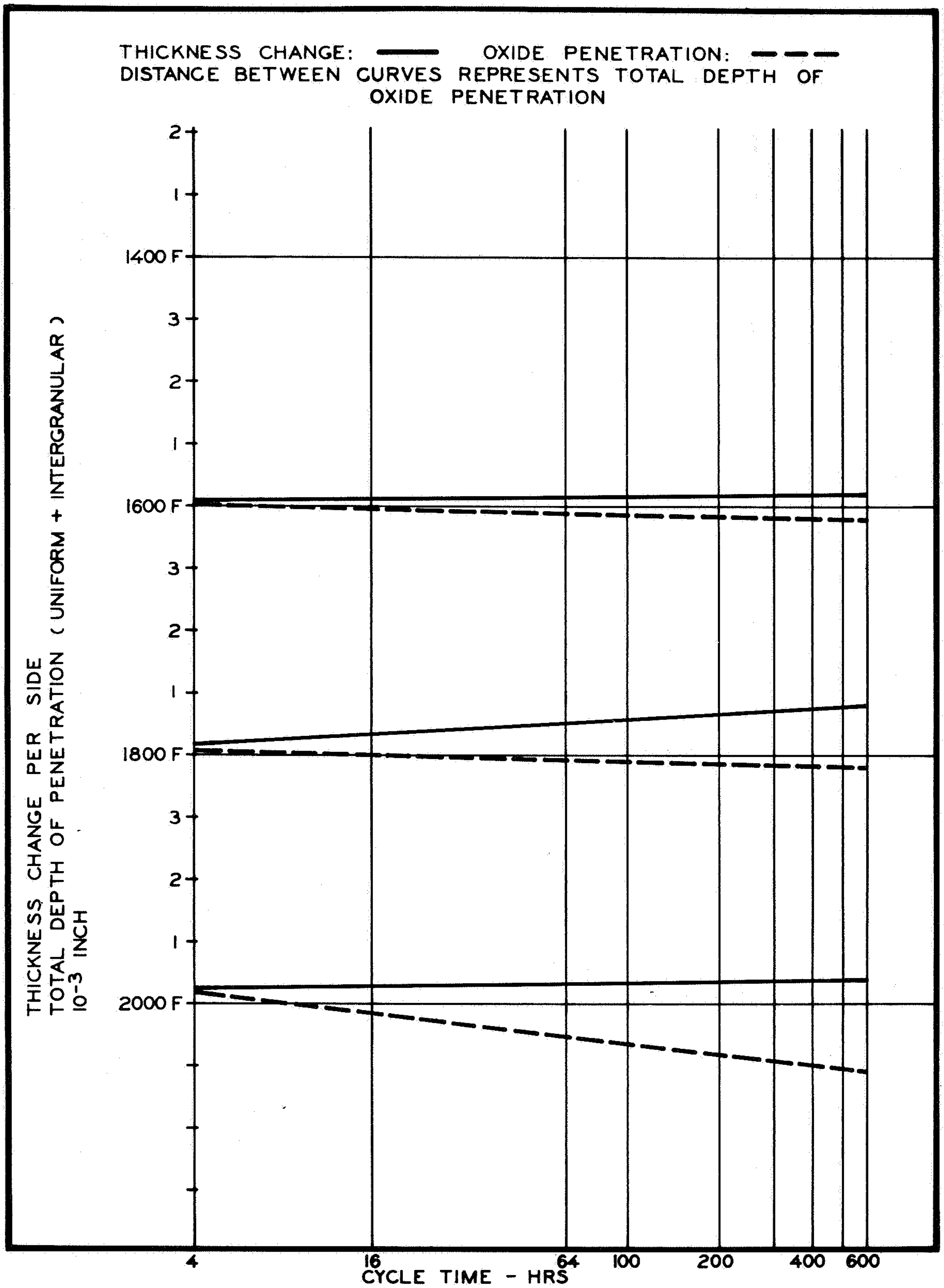


Figure A4-4 Oxidation penetration plot: Alloy 4, Bendel 65-35.

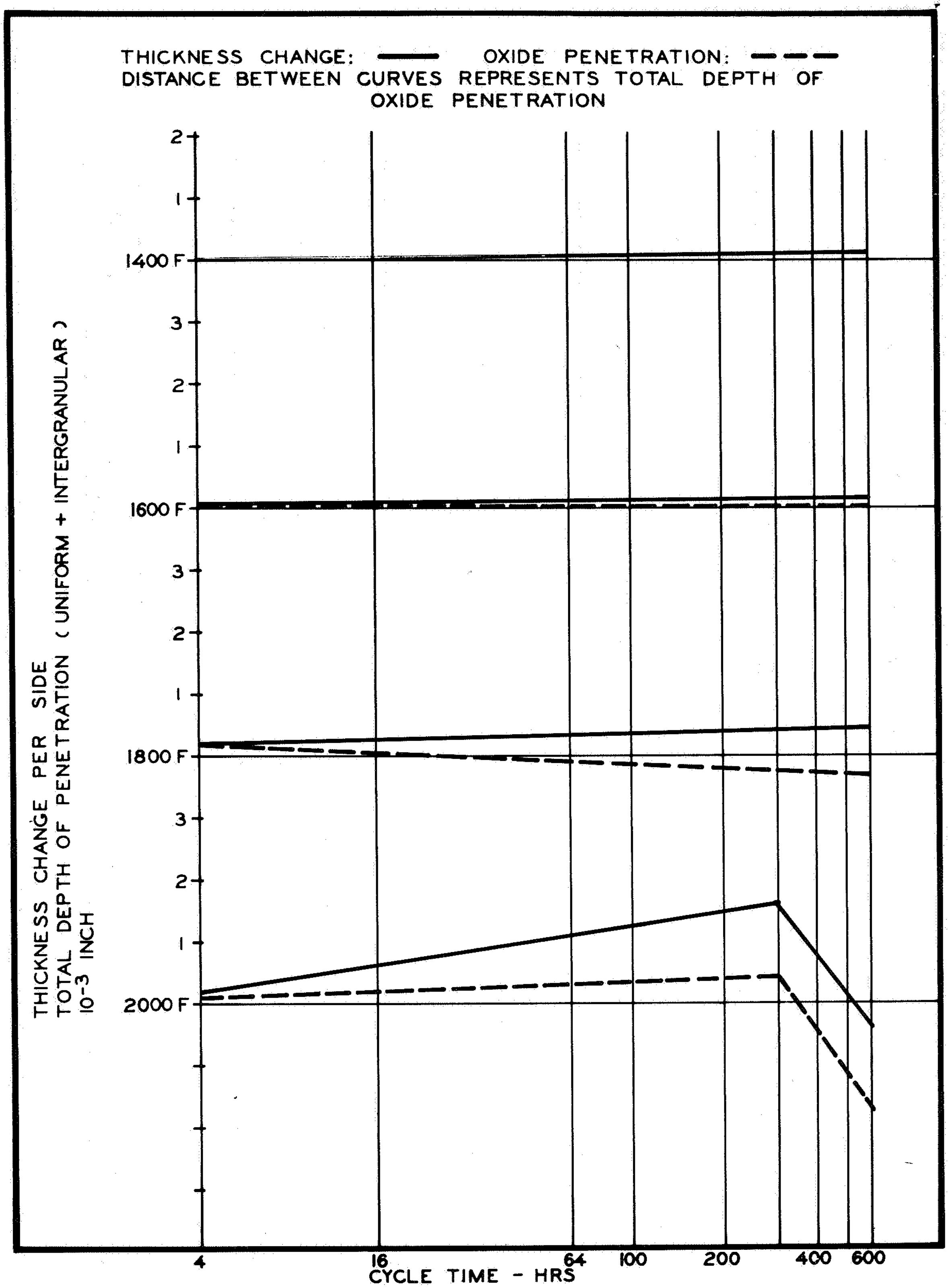


Figure A4-5 Oxidation penetration plot: Alloy 5, Chromel A.

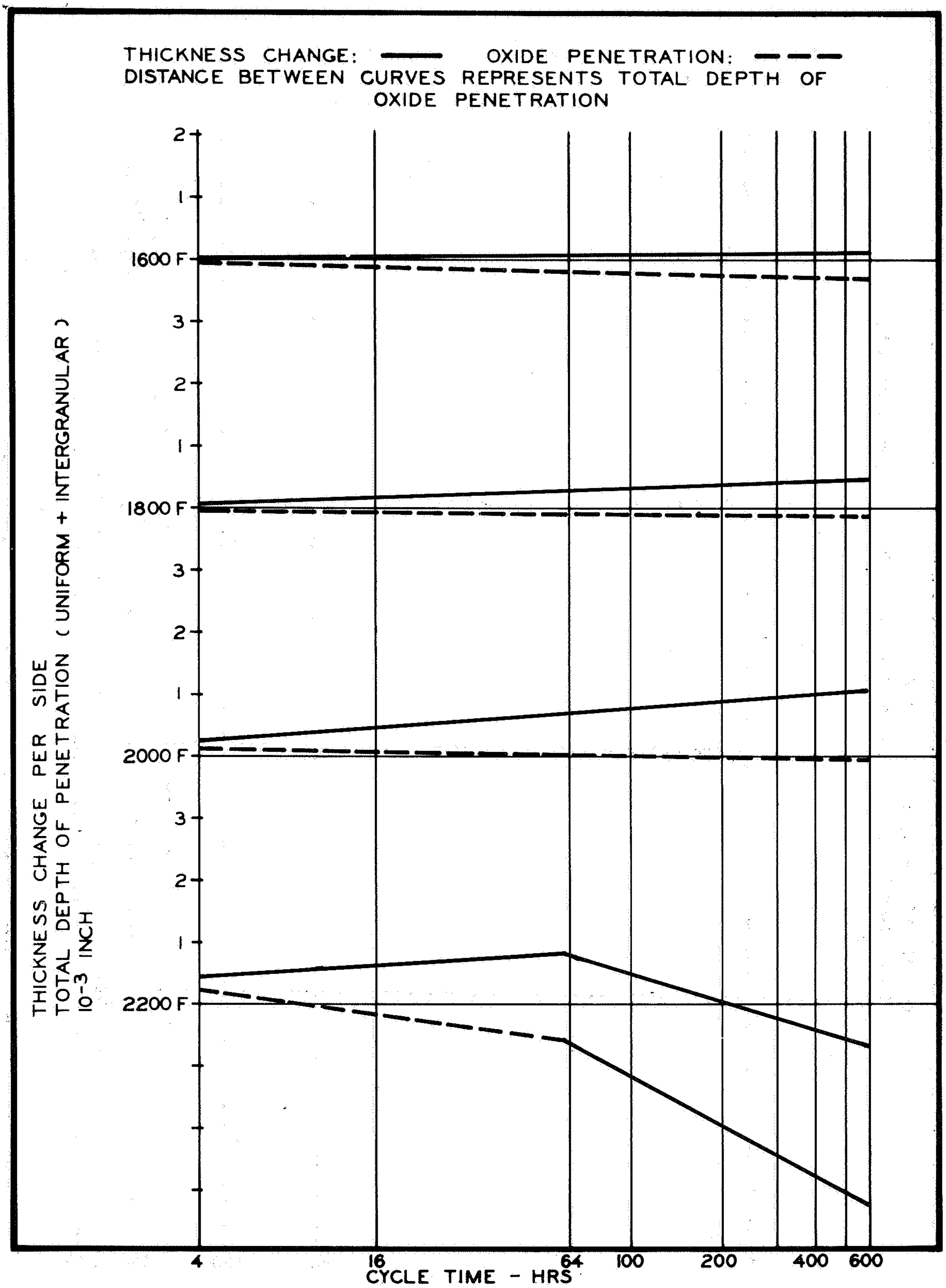


Figure A4-6 Oxidation penetration plot: Alloy 6, DH 242.

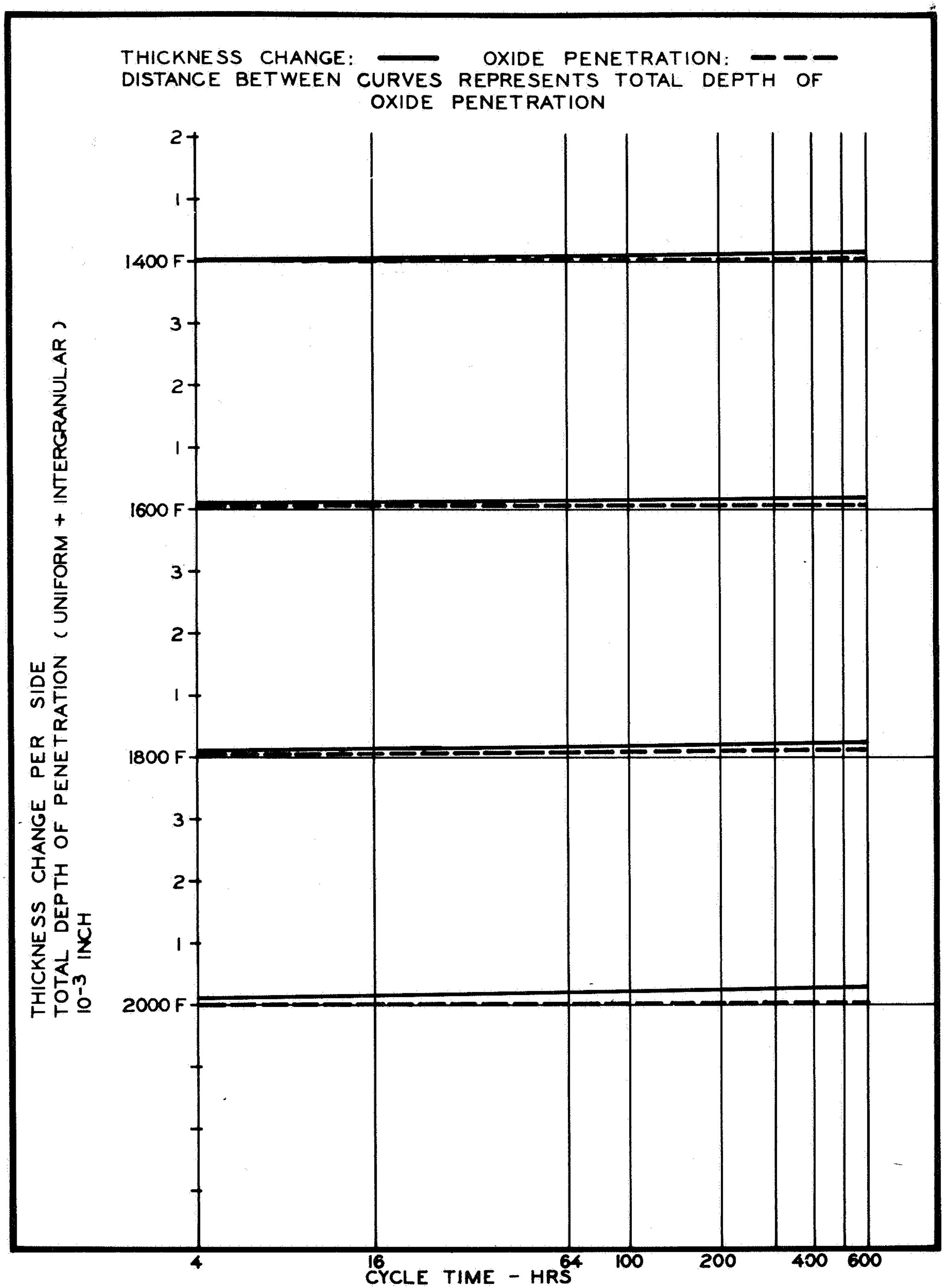


Figure A4-7 Oxidation penetration plot: Alloy 7, GE 1541.

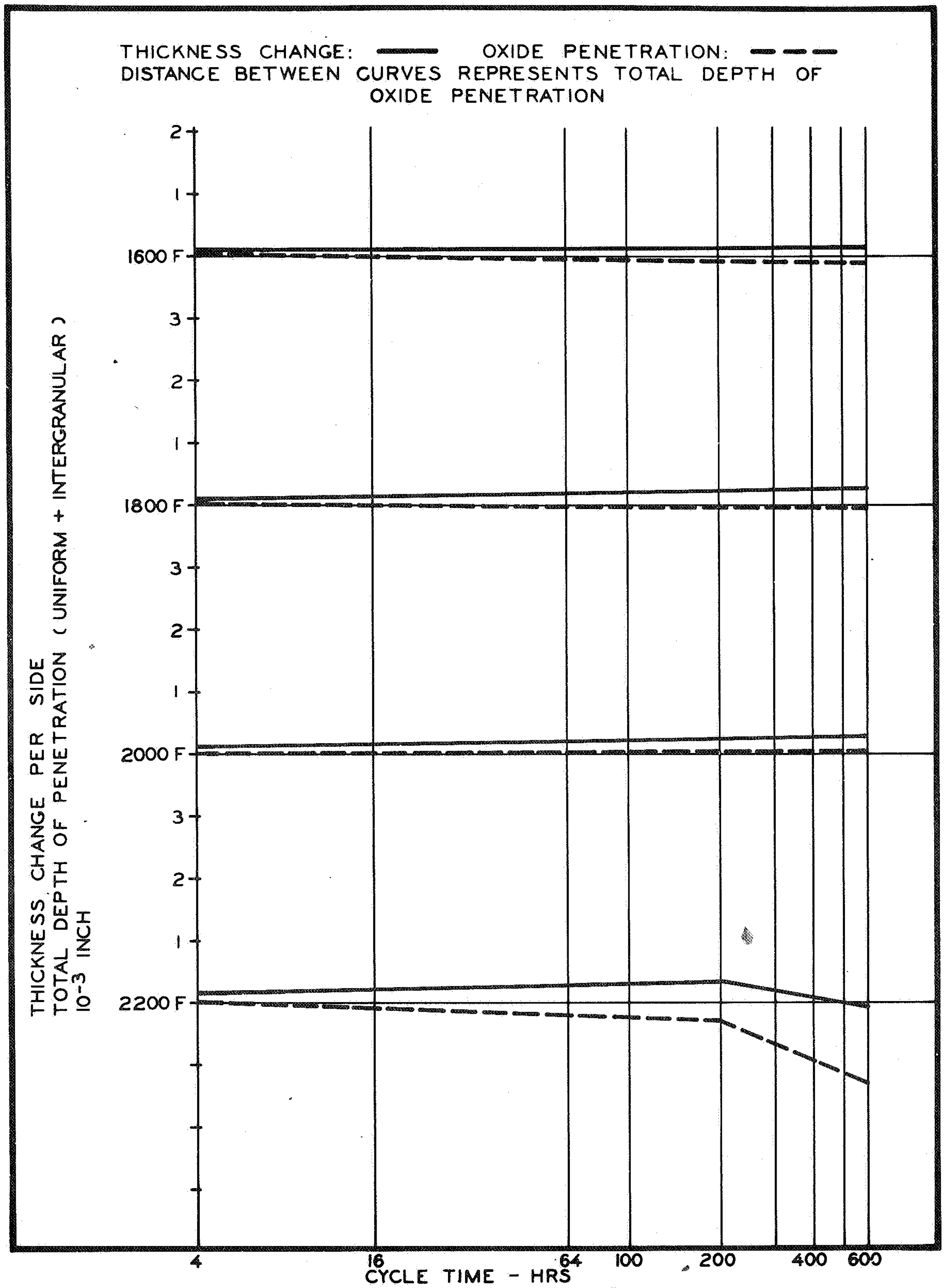


Figure A4-8 Oxidation penetration plot: Alloy 8, Hoskins 875.

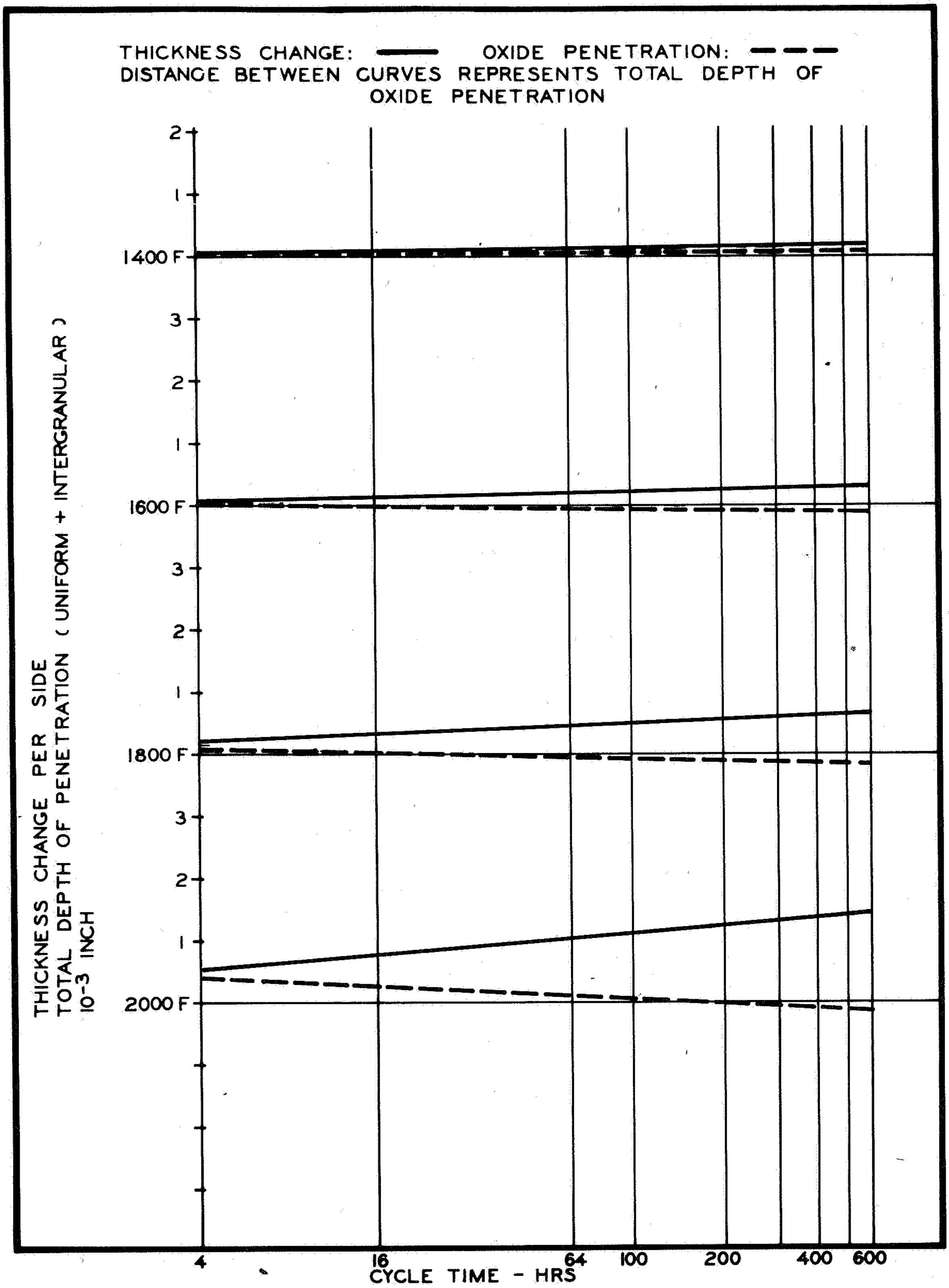


Figure A4-9 Oxidation penetration plot: Alloy 9, RA 333.

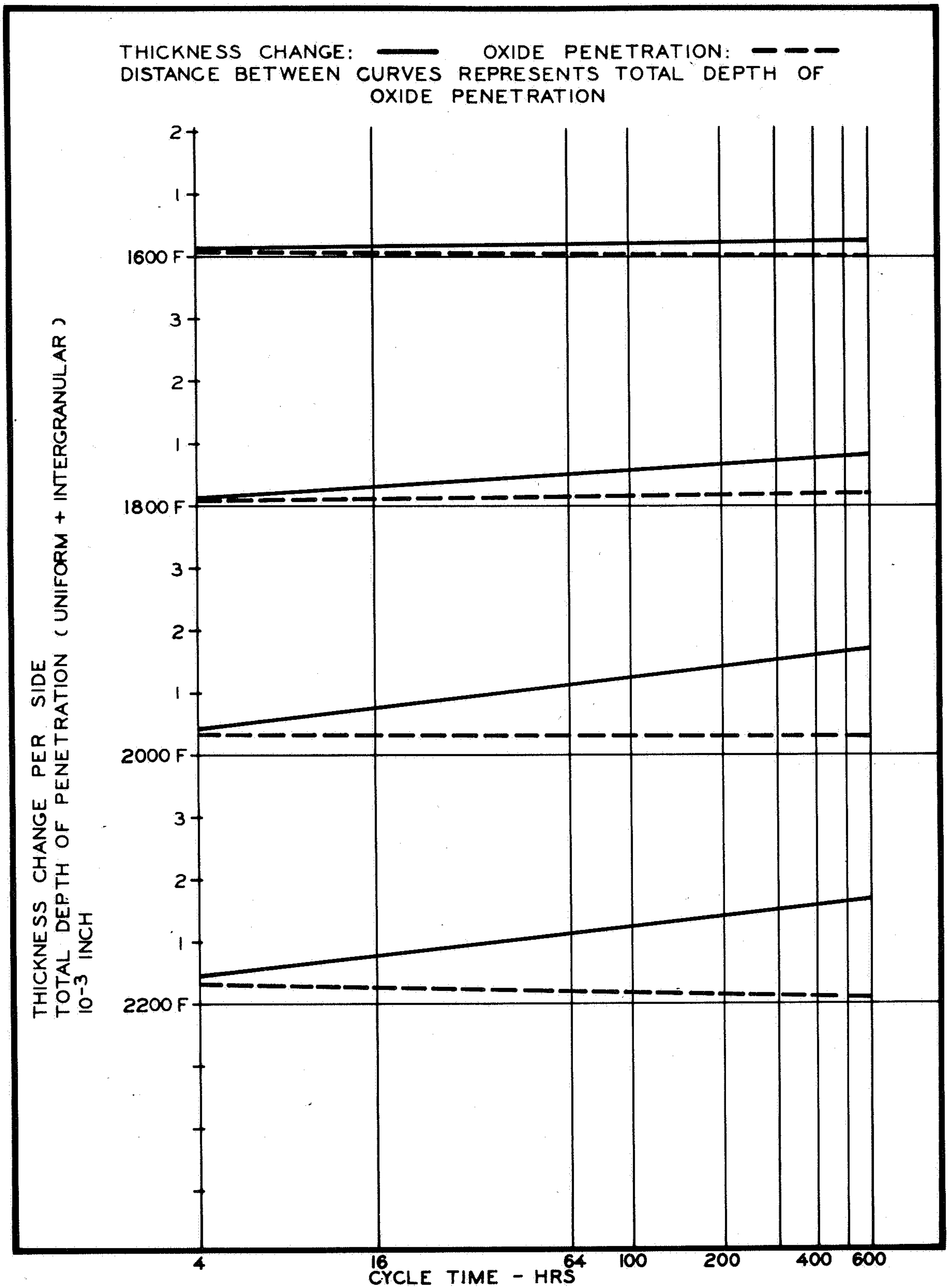


Figure A4-10 Oxidation penetration plot: Alloy 10, Hastelloy X.

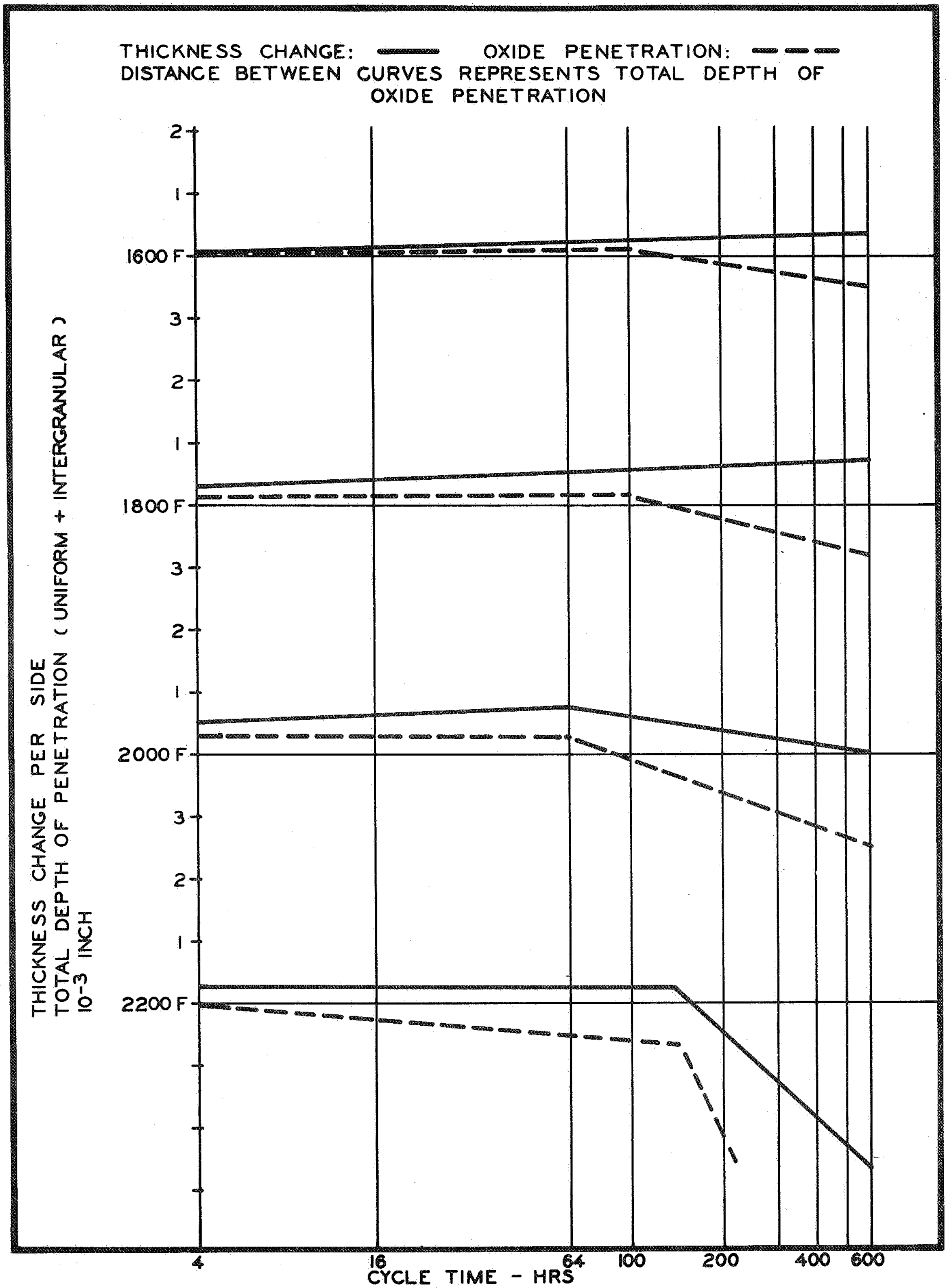


Figure A4-11 Oxidation penetration plot: Alloy 11, Udimet 500.

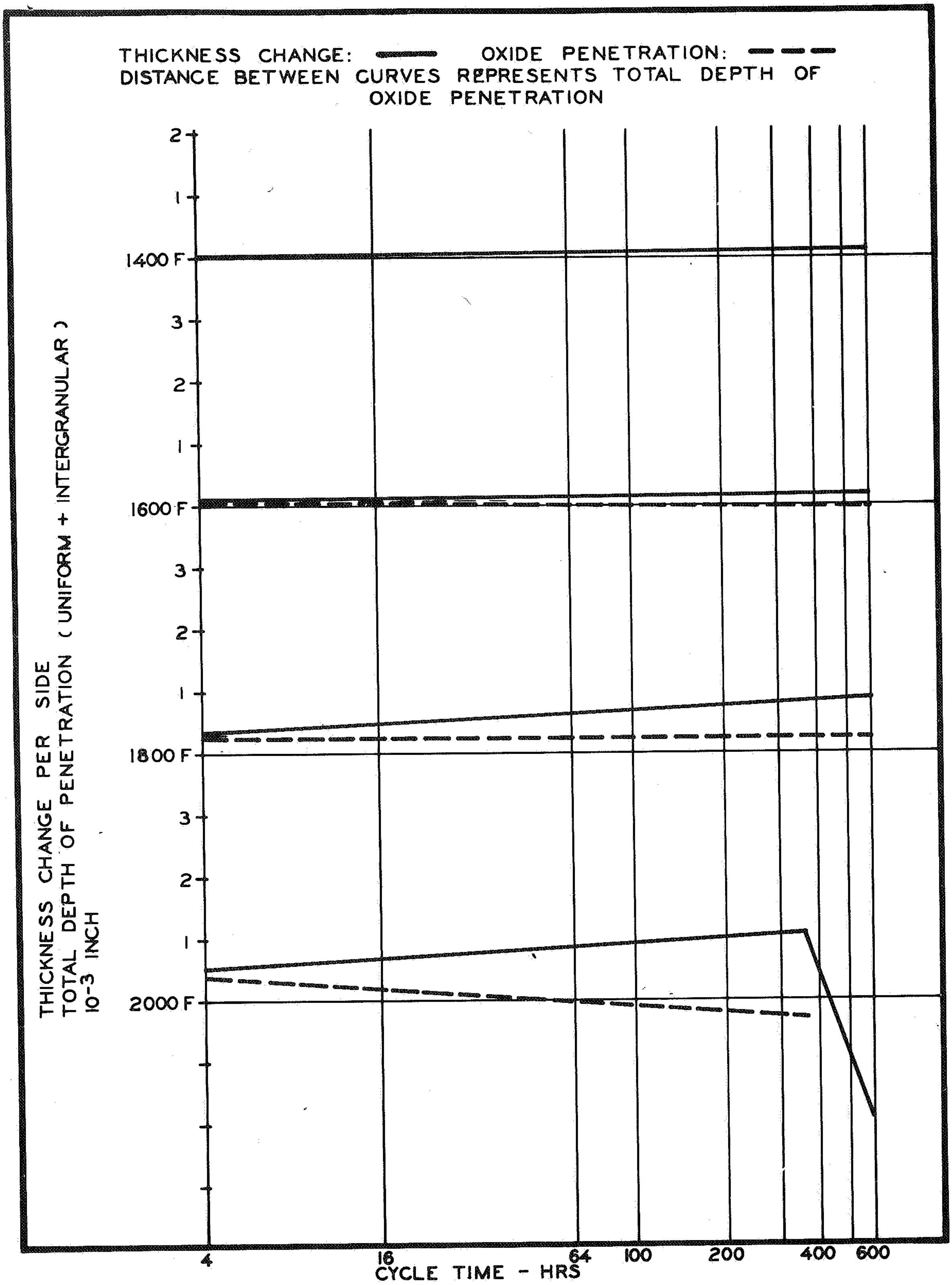


Figure A4-12 Oxidation penetration plot: Alloy 12, Haynes 25.

APPENDIX 5
TENSILE TEST DATA PLOTS

CONTENTS

ALLOY	FIGURE	PAGE
1. N 155	A5-1	136
2. TD nickel	A5-2	136
3. TD nickel-chromium	A5-3	137
4. Bendel 65-35	A5-4	137
5. Chromel A.	A5-5	138
6. DH 242	A5-6	138
7. GE 1541	A5-7	139
8. Hoskins 875	A5-8	139
9. RA 333	A5-9	140
10. Hastelloy X.	A5-10	140
11. Udimet 500	A5-11	141
12. Haynes 25	A5-12	141

Ultimate strength, yield strength (0.2% offset), and percentage elongation are shown for each alloy and test temperature at 100 hours and 600 hours exposure time. Additional tensile tests show comparative mechanical properties for "as-received," "as-sintered," and electron beam welded specimens.

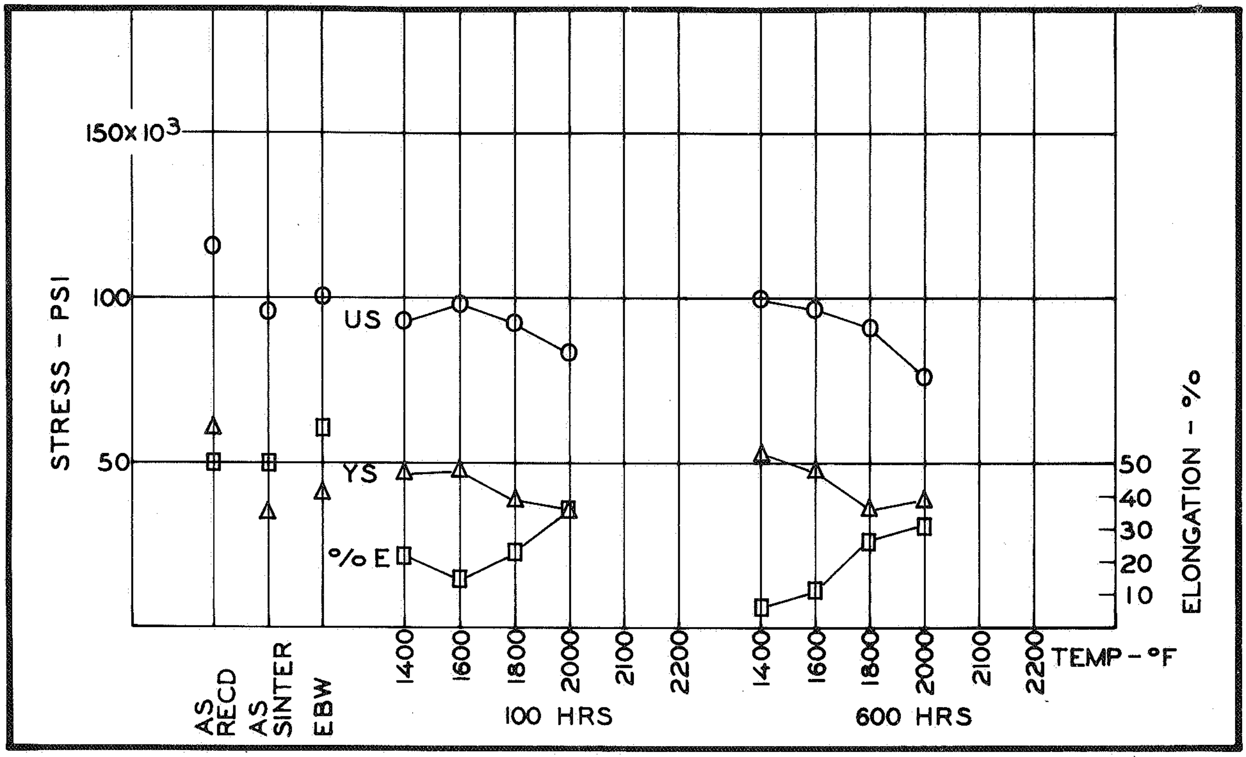


Figure A5-1 Tensile test data plot: Alloy 1, N 155.

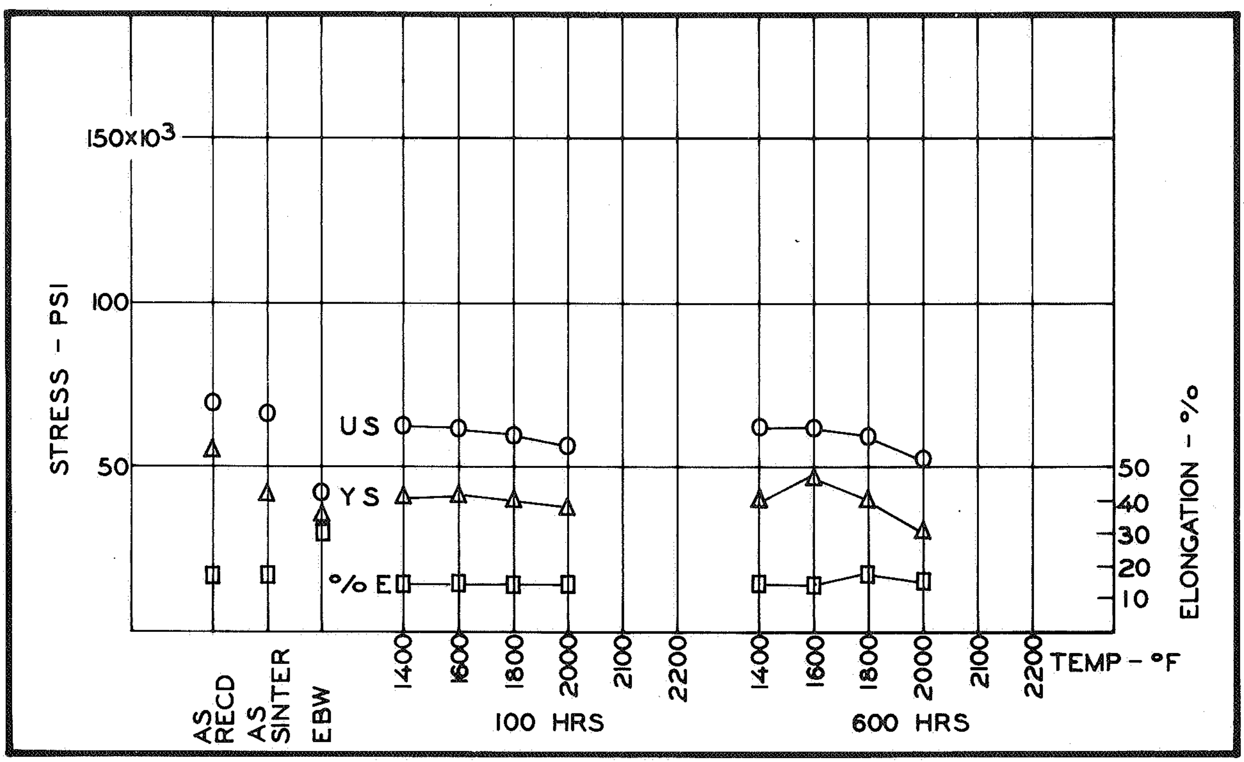


Figure A5-2 Tensile test data plot: Alloy 2, TD nickel.

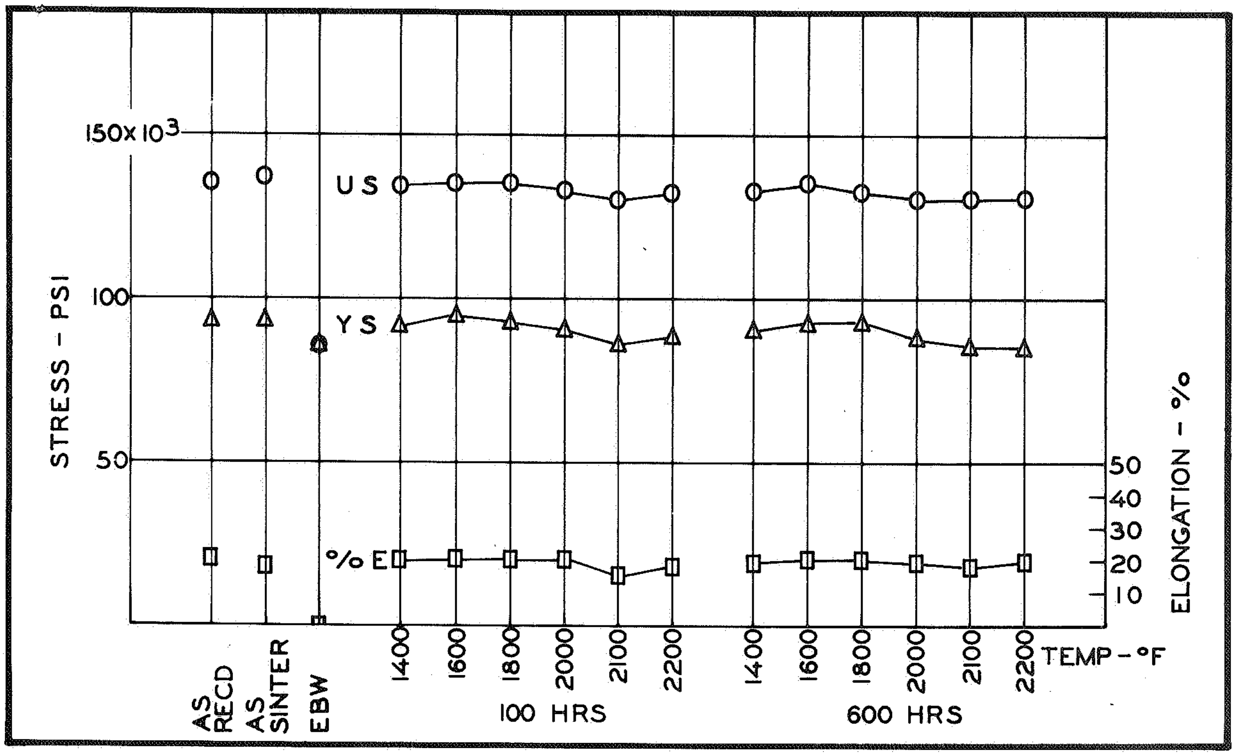


Figure A5-3 Tensile test data plot: Alloy 3, TD nickel-chromium.

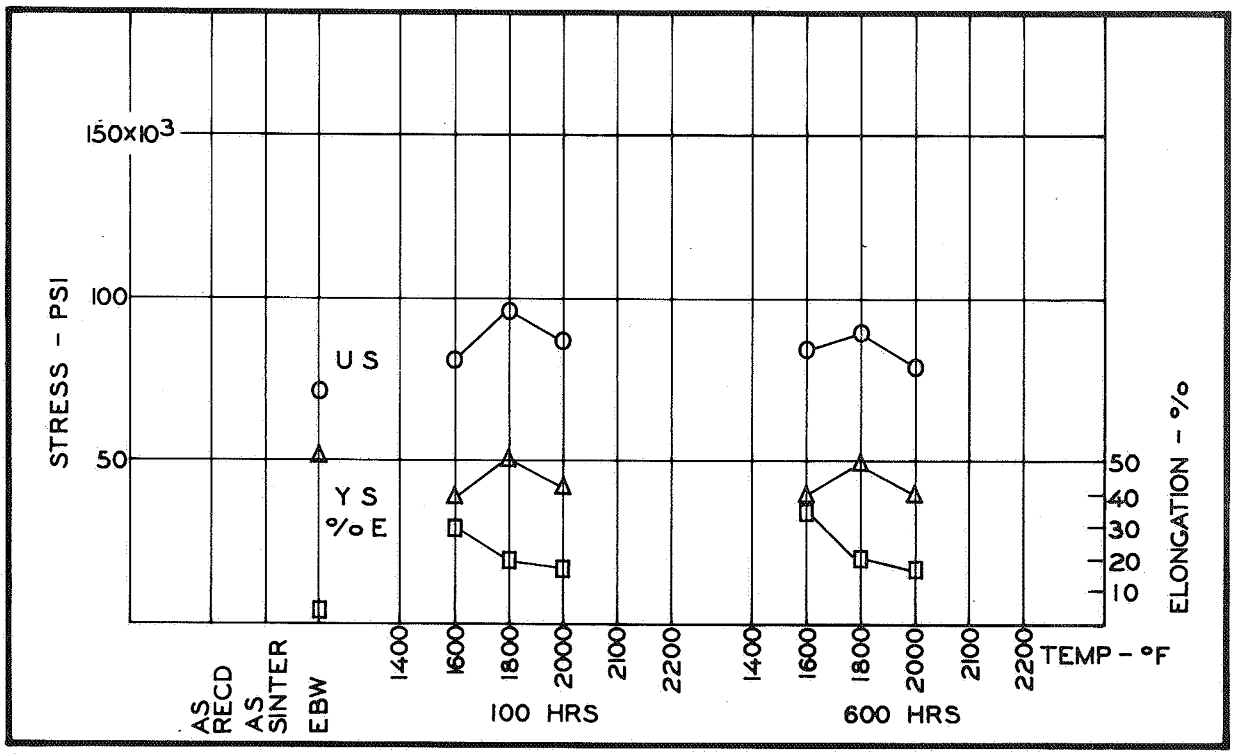


Figure A5-4 Tensile test data plot: Alloy 4, Bendel 65-35.

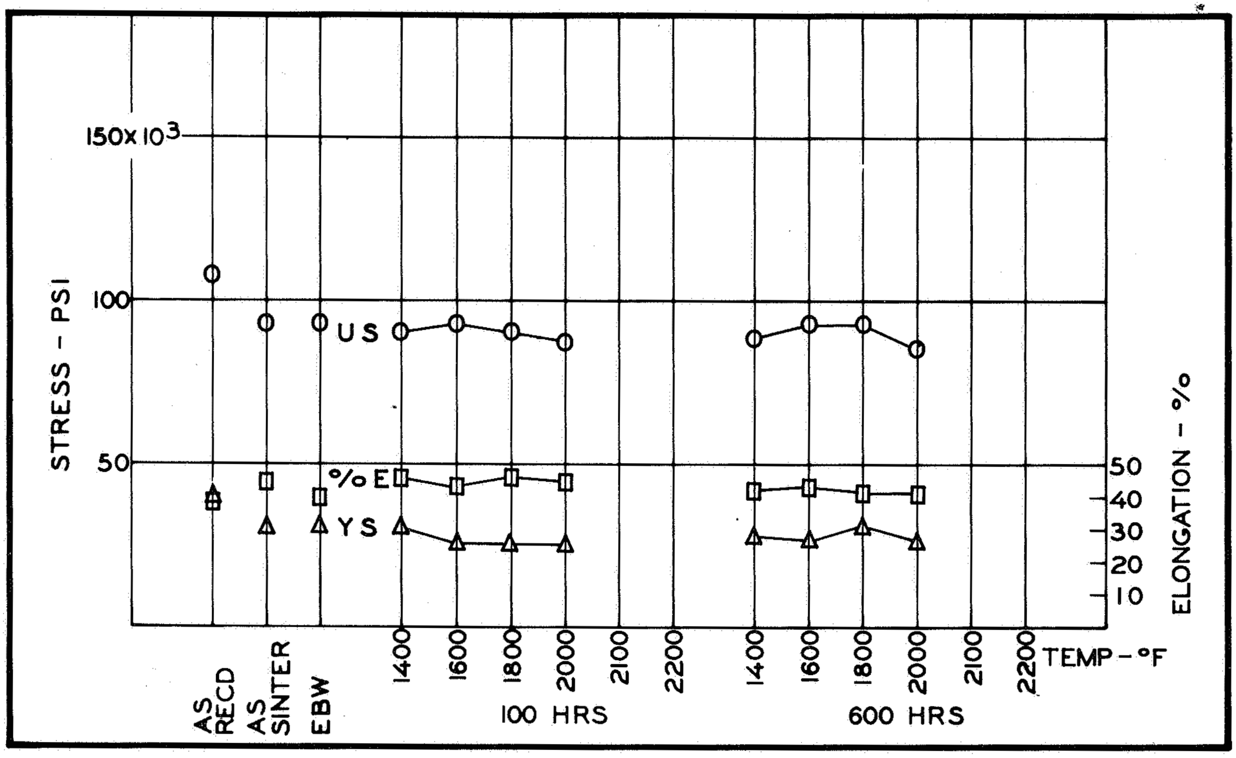


Figure A5-5 Tensile test data plot: Alloy 5, Chromel A.

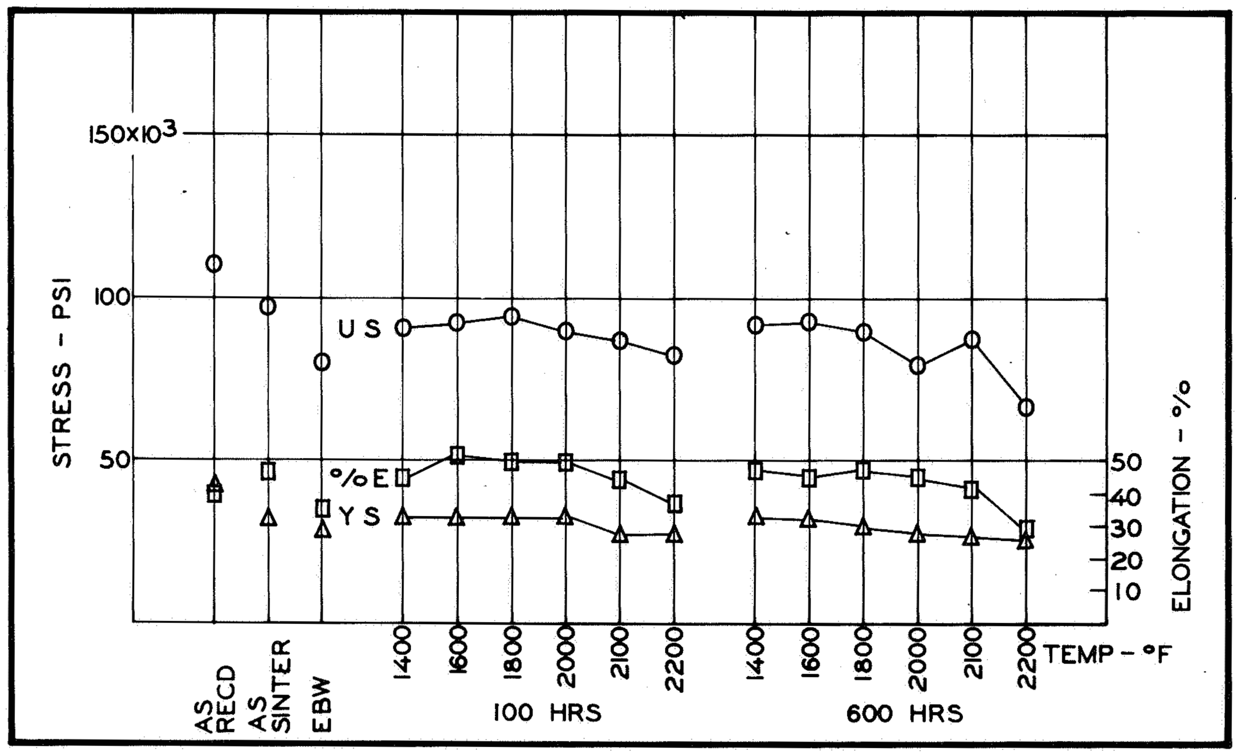


Figure A5-6 Tensile test data plot: Alloy 6, DH 242.

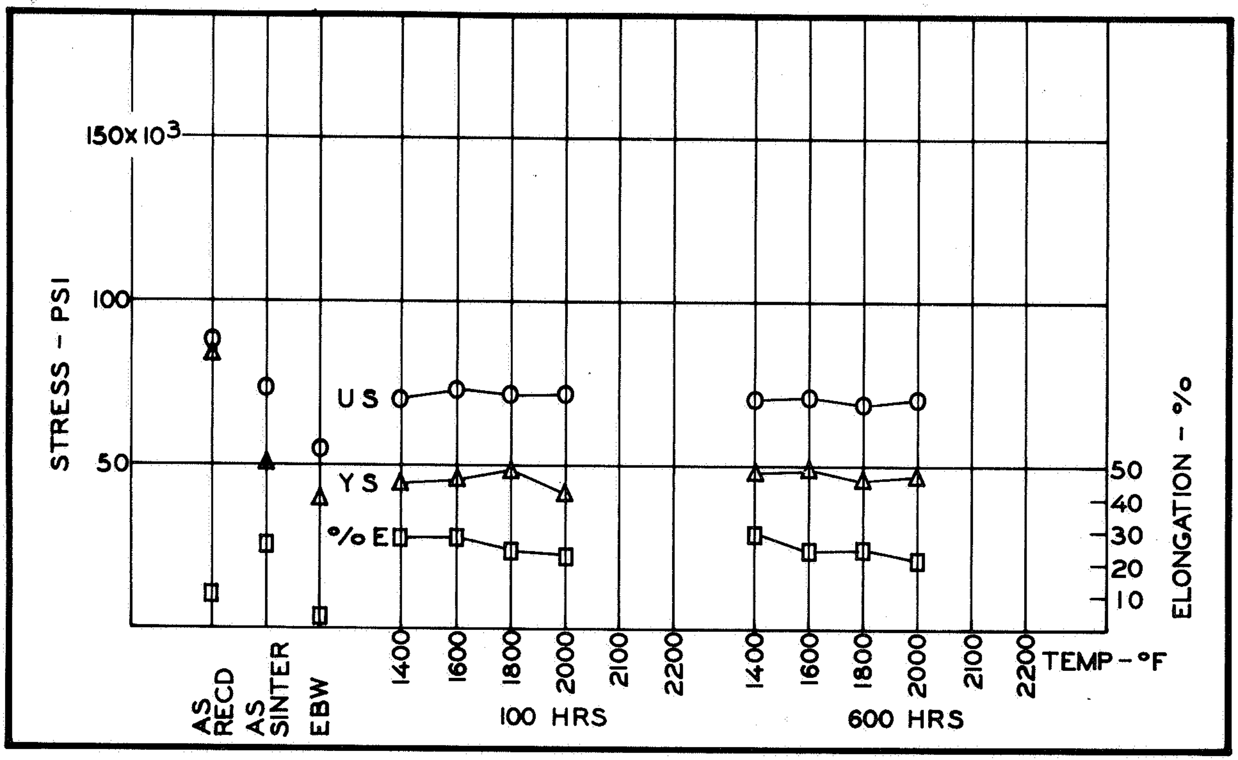


Figure A5-7 Tensile test data plot: Alloy 7, GE 1541.

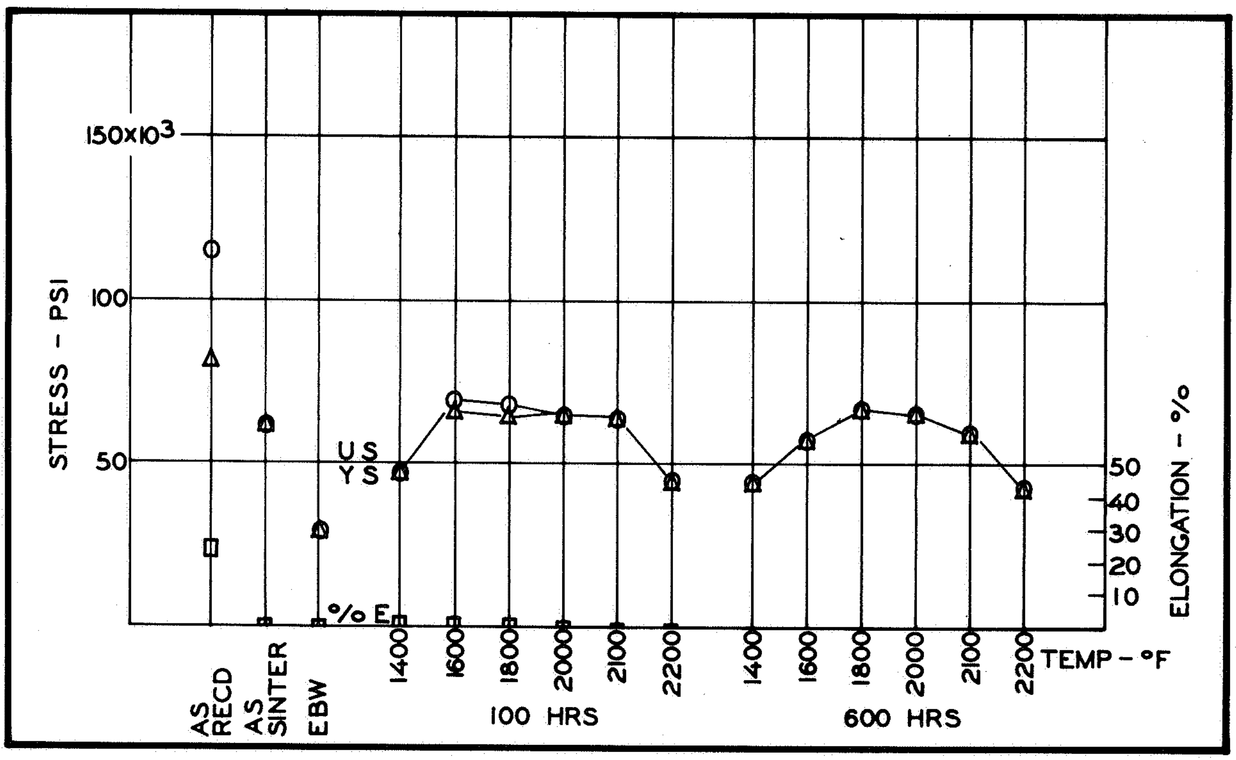


Figure A5-8 Tensile test data plot: Alloy 8, Hoskins 875.

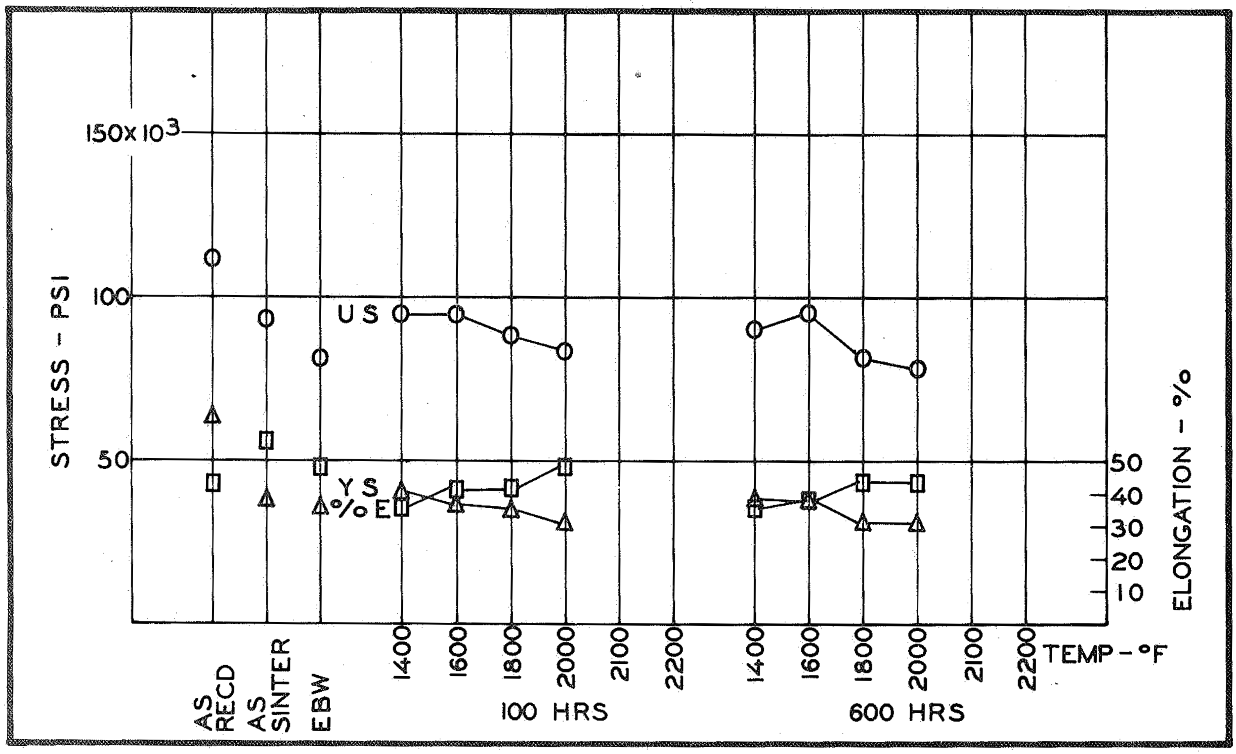


Figure A5-9 Tensile test data plot: Alloy 9, RA 333.

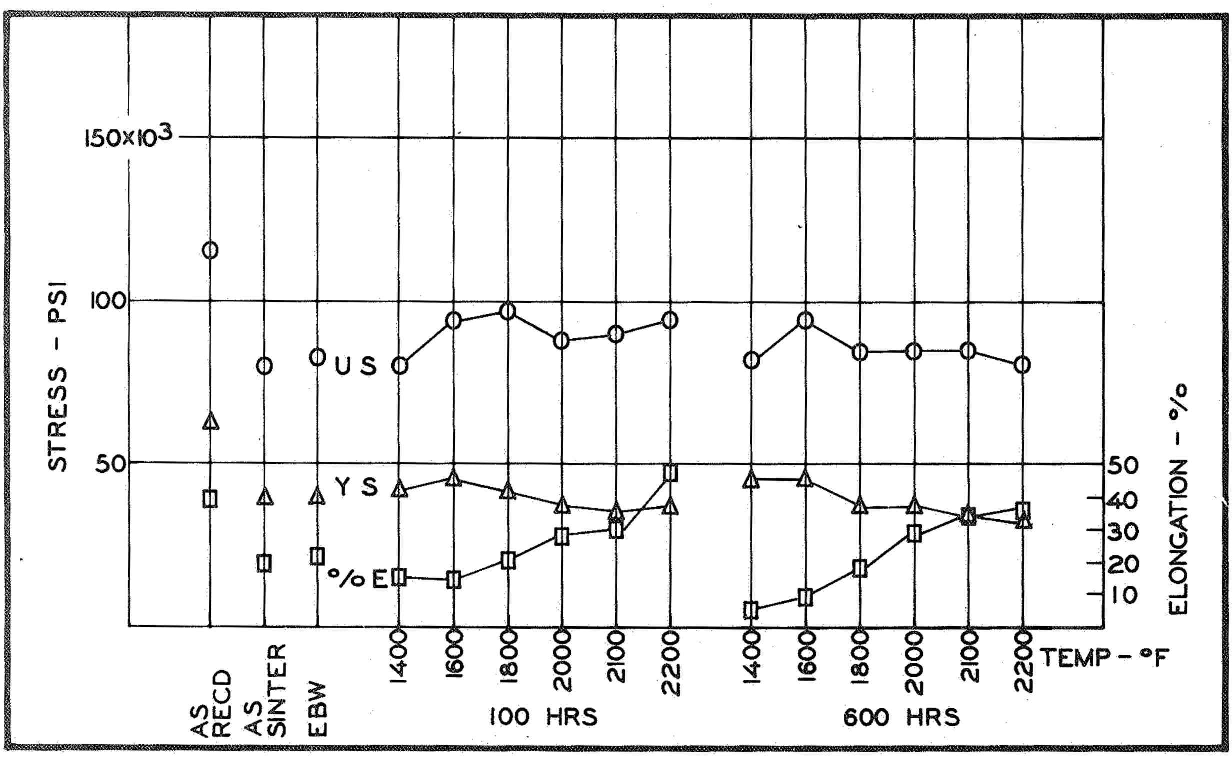


Figure A5-10 Tensile test data plot: Alloy 10, Hastelloy X.

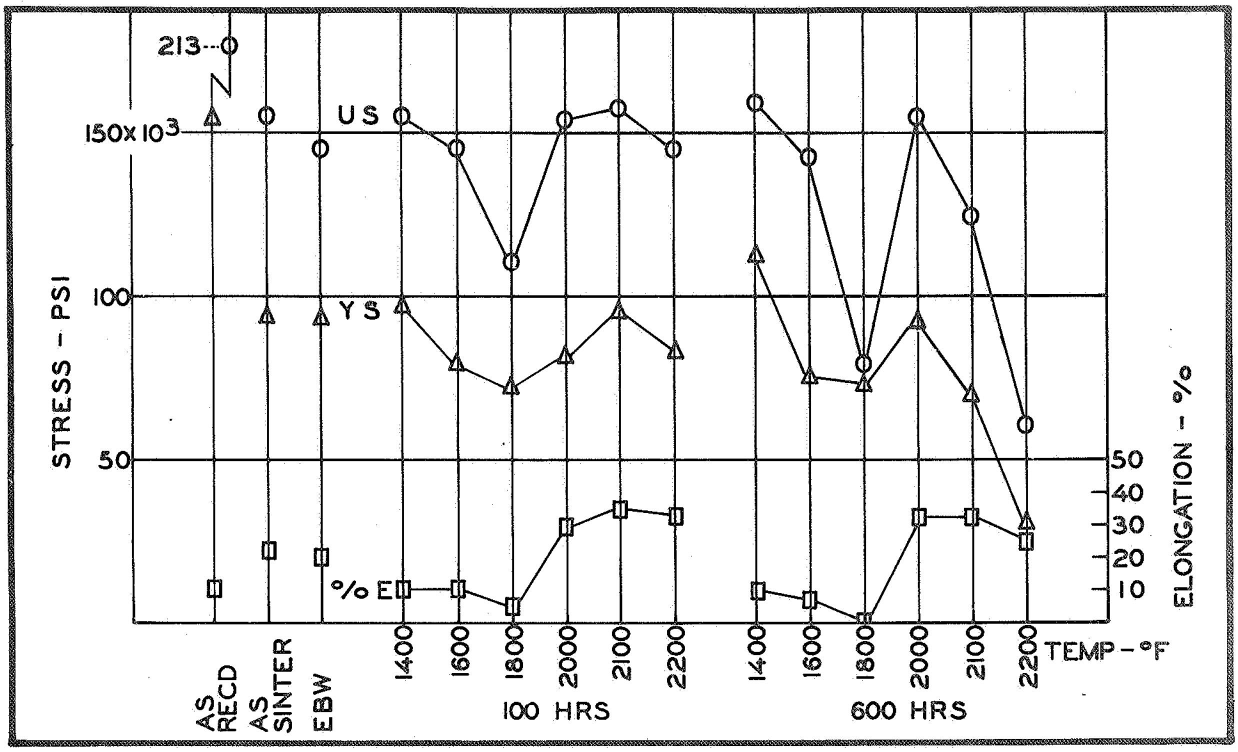


Figure A5-11 Tensile test data plot: Alloy 11, Udimet 500.

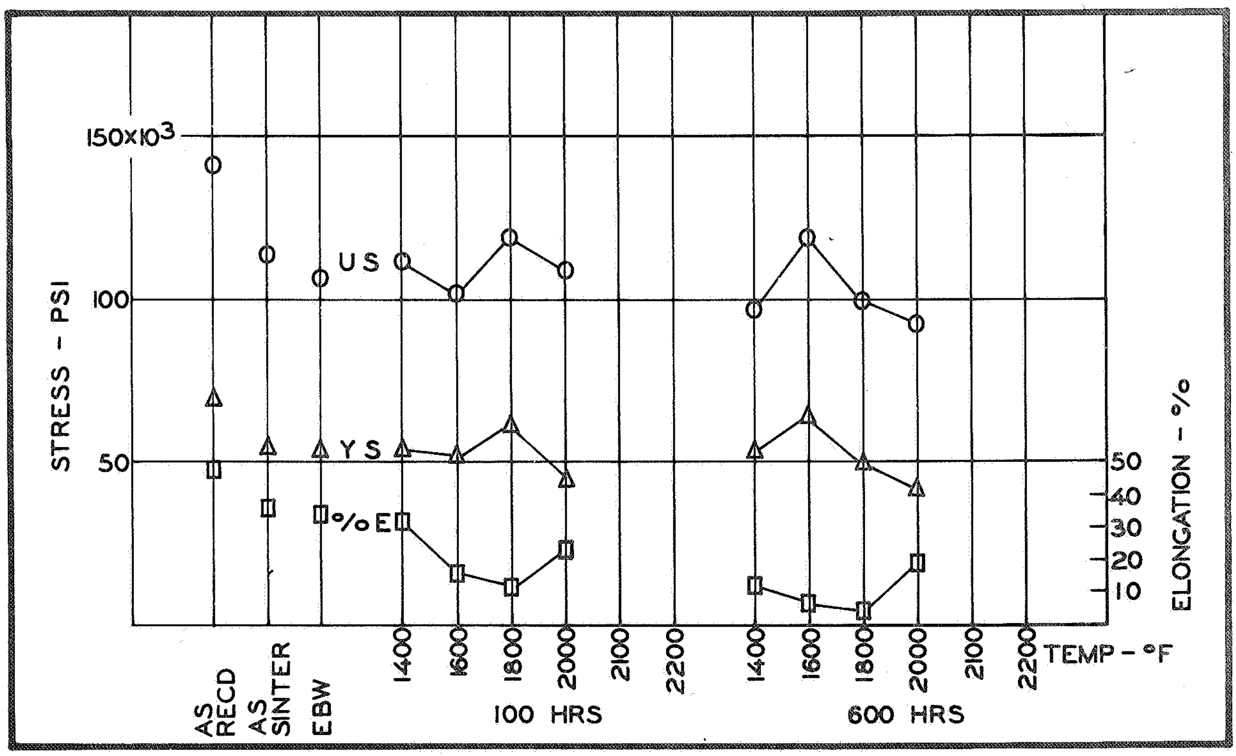


Figure A5-12 Tensile test data plot: Alloy 12, Haynes 25.

CR-930 NASA-Langley, 1967 —— 17

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546